Plate 1. Rothamsted Laboratories for Soil and Plant Nutrition. Erected 1914.

PLANT NUTRITION AND CROP PRODUCTION

BY

E. J. RUSSELL

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FOREWORD

It gives me unusual pleasure to comply with the invitation of the fifteenth lecturer on the Hitchcock Foundation, Sir John Russell, to write a foreword to this little volume, which embodies the Hitchcock Lectures for 1924.

The Hitchcock Lectureship in the University of California was established in 1909 for the purpose of giving the public the benefit of lectures on "popular and scientific subjects." It is an earnest of the generosity and public spirit of the late Charles M. Hitchcock of San Francisco. Since its establishment the Hitchcock Foundation has provided lectures by the following eminent scholars:

1909.	JULIUS STIEGLITZ *University of Chicago*	Chemistry
1910.	AUGUSTUS D. WALLER *University of London*	Physiology
1911.	HARRY FIELDING REID *Johns Hopkins University*	Geology and Geography
1912.	RICHARD M. PEARCE *University of Pennsylvania*	Research Medicine
1914.	HENRY FAIRFIELD OSBORN *Columbia University*	Zoology
1916.	THOMAS H. MORGAN *Columbia University*	Zoology
1917.	ROBERT A. MILLIKAN *University of Chicago*	Physics
	IRVING FISHER *Yale University*	Economics
1918.	GEORGE F. SWAIN *Harvard University*	Civil Engineering
1919.	W. J. V. OSTERHOUT *Harvard University*	Botany
	VITO VOLTERRA *Rome*	Mathematical Physics
1920.	JULES BORDET *Brussels*	Bacteriology
1922.	LAFAYETTE B. MENDEL *Yale University*	Physiological Chemistry
1923.	C. V. L. CHARLIER *Lund, Sweden*	Astronomy
1924.	SIR JOHN RUSSELL *England*	Agriculture

The appointment of Sir John Russell to the Hitchcock Lectureship for 1924 signalized the first occasion on which agricultural science was the lecturer's field. The appointment was made not only because all concerned recognize the superlative importance of agricultural science, and the great progress made in that field in recent years, but because the lecturer, Sir John Russell, embodies in his personality the characteristic type of ability and industry which the agricultural science of this century represents. It was therefore eminently fitting that the Director of the Rothamsted Experimental Station, at Harpenden in Hertfordshire, England, with its more than three quarters of a century of continuous study of plants and soils, constituting the oldest and most celebrated of all agricultural experiment stations, should be chosen to deliver the first series of Hitchcock Lectures dealing with agricultural science. The distinction of Sir John Russell's own contributions to the subject of plants in their relation with soils, in succession to those of his celebrated predecessors, Sir John Bennet Lawes and Sir Henry Gilbert, assured for his lectures a degree of excellence which would commend them to all persons directly or indirectly interested in that field of work. The time is now past for the world to be content with rule of thumb methods and empirical tests in agricultural science. The present and future of that field of endeavor require the application of the imagination and the technique of the trained chemist and physiologist. These difficult problems which confront agricultural scientists, without the methods and imagination of the exquisitely trained investigator must remain sterile and useless for the development and progress of agriculture. It is his devotion to such a view and his unceasing efforts to give

it recognition that commend Sir John Russell so highly to the scientific world.

In the accompanying lectures the author describes the achievements which have resulted from the efforts of investigators who sought to determine the relations of plants to their environment. These lectures have been so well received in this State and other states of our country that the University of California feels itself honored to be the means of making them available to the scientific and popular world. We congratulate ourselves on the opportunity of adding this tribute to the sterling character, ability, and industry of one of England's sons to the praise he has won so abundantly in his own country and in other lands.

W. W. CAMPBELL.

Chapter I

THE STUDY OF PLANT NUTRIENTS

The sources from which plants derive their substances attracted students of nature long before the era of experimentation began. Two of their speculations survived for some hundreds of years and exercised a profound influence on natural philosophy in its early days. One, the older, attributed to Thales (B.C. 600), was to the effect that plants derived all their food and all their substance from water; the other was to the effect that they fed upon decaying animal or vegetable matter in the soil, on the assumed principle that plants, like all other living things, could feed upon materials of like nature with themselves but not on materials of unlike nature.

The view that water is the food of plants was tested experimentally about 1620 and convincingly proved by the very beautiful and satisfying experiment of van Helmont:

> I took an earthern vessel in which I put 200 pounds of soil dried in an oven, then I moistened with rain water and pressed hard into it a shoot of willow weighing 5 pounds. After exactly five years the tree that had grown up weighed 169 pounds and about three ounces. But the vessel had never received anything but rain water or distilled water to moisten the soil when this was necessary, and it remained full of soil, which was still tightly packed; and, lest any dust from outside should get into the soil, it was covered with a sheet of iron coated with tin but perforated with many holes. I did not take the weight of the leaves which fell in the autumn. In the end I dried the soil once more and got the same 200 pounds that I started with, less about two ounces. Therefore the 164 pounds of wood, bark, and root, arose from the water alone.

Few experiments show more clearly the need for caution in interpreting results. The experiment was quite good but the conclusion quite wrong: van Helmont completely missed the part played by the air, as indeed he might well do, the air being then ignored by philosophers. To himself and many of his contemporaries the conclusion seemed irresistible that plants are composed of water and therefore feed on water. But his experiment was wholly without effect on agriculture.

TABLE 1. WOODWARD'S EXPERIMENTS (1699)
(Phil. Trans., 1699, vol. 21, p. 382.)

Source of water	Weight of plants: When put in	Weight of plants: When taken out	Gain in 77 days
	Grains	*Grains*	*Grains*
Rain water	28¼	45¾	17½
River Thames	28	54	26
Hyde Park conduit	110	249	139
Hyde Park conduit + 1½ ounces garden mould	92	376	284

Even if the farmers of the day had heard of the result they would not have believed it, for they knew from experience that water is not the one and only food for plants; without good soil and good manure they would get no crops.

It was nearly eighty years before scientific proof was forthcoming of the incorrectness of van Helmont's view. In 1699 Woodward made the first water culture experiments on record and showed that the growth of spearmint (*Mentha spicata*) was much less in rain water (the purest form of water he could get) than in impure water; while the best results were obtained when some garden soil was shaken up with the water.

The nutrition of the plant therefore depended on something additional to water which apparently came from the soil. This view accorded with the farmer's experience. Experiments by other workers showed that certain definite substances were helpful if not essential to plant nutrition; Glauber in 1656 found that nitrates greatly increased plant growth; Home in 1756 in the first recorded pot experiment proved the value of a potassium salt, while the Earl of Dundonald in 1795 showed that phosphates

TABLE 2. FRANCIS HOME'S POT EXPERIMENTS (1755)
(Principles of Agriculture and Vegetation.)

	Number of ears of barley	
	Good soil	Poor soil
"Plain earth"	17	10
Saltpeter	15	11 (better ears)
"Vitriolated tartar"	29	
Epsom salt (K_2SO_4)		13 (equal to saltpeter)
Oil of olives	9 (very large)	
Lime+spirit of niter+oil of olives		16 (best)

are useful. These results were, however, so completely shrouded in a maze of inaccurate and irrelevant statement that no agriculturist could realize their value, nor was there any reason why they should be selected out from the erroneous results. The eighteenth century was not a period of logical development in science: on the contrary, it was thought that discoveries might be made by chance and by newcomers without the special training and equipment nowadays deemed necessary. Joseph Priestley, one of the most distinguished men of his age, wrote:

I do not think it at all degrading to the business of experimental philosophy, to compare it, as I often do, to the diversion of

hunting, where it sometimes happens that those who have beat the ground most, and are consequently the best acquainted with it, weary themselves, without starting any game, when it may fall in the way of a mere passenger.[1]

And as a concrete example he writes in his History of Electricity (1767):

> It requires no great stock of particular preparatory knowledge; so that any person that is tolerably well versed in experimental philosophy, may presently be upon a level with the most experienced electricians . . . . several raw adventurers have made themselves as considerable as some who have been, in other respects, the greatest philosophers. I need not tell my readers of how great weight this consideration is, to induce him to provide himself with an electrical apparatus.

Progress was, however, steadily made, and by the close of the eighteenth century the part played by the air in plant growth had been established. The data for a first solution of the agricultural problem had all been obtained and de Saussure's masterly summary followed in 1804,[2] but curiously enough no one saw its bearing on agricultural science. Agricultural chemists of one hundred years ago could see no practical application of the work on plant nutrition then in progress: it was apparently academic and remote from practice; the views and experimental results of one worker were at variance with those of others; there seemed no hope, and there was little attempt, to reconcile them. Farmers and agricultural workers kept to the view that farmyard manure was the food of plants, although admitting that other things might help, especially animal products, bones, blood, wool, or vegetable products like composts, turf,

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[1] From the Dedication and Preface to Experiments and Observations on Different Kinds of Air, and Other Branches of Natural Philosophy connected with the subject. In Three Volumes; being the Former Six Abridged and Methodized, with many additions.

[2] Theodore de Saussure, Recherches chimiques sur la végétation (Paris, 1804).

and certain mineral substances such as salt, lime, wood ashes, etc. No one knew how to use any of these substances: no explanation could be given of the numerous failures or of the undoubted successes. The scientific work of the time was not helpful; and as always happens in such cases empiricism became linked with speculation, and plant nutrition remained something of a mystery. The animal and vegetable products were of

TABLE 3. STATISTICS OF A ROTATION. BOUSSINGAULT (1841)
(Ann. Chim. Phys., 1841, series 3, vol. 1, p. 208.)

	Weight in hundred kilograms per hectare of			
	Dry matter	Carbon	Nitrogen	Mineral matter
1. Beets	31.7	13.6	0.5	2.0
2. Wheat	30.0	14.3	0.3	1.6
3. Clover hay	40.3	19.1	0.8	3.1
Turnips (catch-crop)	7.2	3.1	0.1	0.5
4. Wheat	42.1	20.0	0.4	2.3
5. Oats	23.5	11.8	0.3	1.1
Total during rotation	174.8	81.9	2.4	10.6
Added in manure	101.6	36.4	2.0	32.7
Difference not accounted for, taken from air, rain, and soil	+73.2	+45.5	+0.4	−22.1

like nature with the plant, and the weight of experience was with the old hypothesis that it was these, and not things differing in nature, that constituted the food of plants. But in 1834 Boussingault (pl. 2) introduced the method of exact field experiments. He laid out carefully manured plots, weighed and analyzed the manures applied and the crops grown, and then drew up a balance sheet showing what had been put into the soil and what had been taken out by the plant. He thus applied in the field the statistical methods which de Saussure had

used with great advantage in plant physiology and he assembled a mass of exact data which could not fail to give the solution of the problem. His papers are models of lucid thought and exposition, and clearly illustrate the difference in outlook and method between the eighteenth and nineteenth centuries: they should be read by every student of the subject. His book, Rural Economy, is one of the most interesting that has been written on our subject. A very great advance soon followed, though it was not Boussingault who made it. The year 1840 is a turning point in the history of agricultural science: it was then that Liebig[2a] (pl. 2) brought together many of these scattered observations and pieced the apparently incompatible and disjointed fragments into a harmonious whole. He saw, more clearly than anyone before, the bearing on crop production of the facts that phosphates, potassium compounds, and ammonium salts increase the growth of plants, and he boldly announced that the food of plants is not decaying animal or vegetable matter, and not farmyard manure, but the ashes of plants: potassium, sodium, magnesium, and calcium compounds; and certain atmospheric constituents, carbon dioxide and ammonia. The atmospheric foods are available in unlimited amounts but the mineral or ash foods are not: they can be removed from the soil by cropping and their loss renders the soil infertile. If these ash constituents are restored the soil regains its fertility. Farmyard manure certainly was an effective fertilizer; not, however, because it was of like nature with the plant, but because it contained the ashes of the plant. The application of farmyard manure in his view was quite unnecessary; it was only a cumbersome way of adding

[2a] Chemistry in its Application to Agriculture and Physiology (1840).

essential potassium, calcium, and magnesium compounds. His essay has all the simplicity of a work of great genius; looking back one wonders why the discovery was so long delayed, but from the point of view of 1840, obsessed with the importance of farmyard manure, the right perspective was very difficult to attain.

The importance of Liebig's work is twofold. From the scientific point of view it was a brilliant piece of simplification and of synthesis, in that it did away with the old mystery that plants could be nourished only by substances of like nature, and put in its place the simpler but much more wonderful view, that plants feed upon simple mineral and gaseous substances and build them into highly complex products. The whole process now became susceptible of investigation.

From the practical point of view the importance of the work lay in the possibility it afforded for improving the manuring of crops. The standard manure was farmyard manure, but it could not be obtained in sufficient quantities to give the higher productiveness that the newer agricultural systems and the more settled social conditions were making possible. If Liebig's views were correct, the ash constituents could be used instead; chemists could discover them by analysis and thus definitely guide the farmer in the manuring of crops. Further, Liebig saw that it might not be necessary always to add all the ash constituents: he maintained that the crop was limited at any time by the one present in minimum amount, and it rose or fell in exact proportion as this one rose or fell. Manuring, in short, appeared as a simple application of chemistry.

Liebig, in an effort to develop the practical aspects of the subject, made up a patent manure. Unfortunately it failed, and it stands as a warning to the scientific

investigator that laboratory results, however valuable in themselves, can rarely be translated direct into practice. There is almost always need for an investigation in the subject intermediate between the laboratory and the farm, to which Americans have given the expressive name 'agronomy' first used in English about one hundred years ago.

Meanwhile Liebig's work had attracted the attention of John Bennet Lawes (pl. 2), a young English squire fresh from Oxford, combining a keen experimental turn of mind with sound business and farming instincts. He was born in 1817 when Europe was just emerging from a long devastating series of wars such as seem to afflict her every hundred years, and his childhood and youth were passed in the terrible period of distress which followed their termination. So far as comparisons are possible the suffering seems to have been worse then than now, at any rate in England; many farmers became bankrupt, and agriculture was threatened with ruin. Lawes' ancestral home (pl. 3) was one of England's stately mansions, a beautiful Jacobean house set in a background of woods in the pleasant county of Hertfordshire, but he saw that if he would keep it he must get more wealth out of his farm. He therefore experimented with manures to increase the crops, and on varieties of sheep to see which would fatten most quickly. Two simple field experiments made his fame and his fortune. He tried bonedust as a manure for turnips (a highly important crop for sheep food) but obtained no satisfactory results. Like other farmers he knew how useful bonedust was on many soils, but unlike most farmers and landowners of the day he knew sufficient chemistry to realize that it contains an insoluble calcium phosphate which can, on treatment

PLATE 3. Rothamsted: the Home of John Bennet Lawes.

with acids, be converted into a soluble phosphate then called superphosphate of lime. Accordingly, he began in 1839 a series of experiments in which bones decomposed by acids were applied as fertilizer to crops. The new product proved much better than the untreated bone. Lawes further realized that calcium phosphate from any other source would be converted into the same soluble superphosphate on treatment with acid, and so from the outset he included mineral calcium phosphate in his trials, with very satisfactory results.[3] The experiment had at the time only limited practical value, as calcium phosphate was then obtainable in quantity only from bones, the large deposits of rock phosphates not having been discovered. As we shall soon see, a remarkable practical application came later.[4]

The second field experiment was directly stimulated by Liebig's essay. Lawes was apparently prepared to admit the necessity for supplying the crop with the mineral or ash constituents but he was entirely unwilling to agree that the nitrogenous nutrients might be derived wholly from the air as Liebig had insisted. In a series of experiments on wheat on the Broadbalk field, he showed that wheat fertilized with ash constituents gave no better crop than wheat without manure; but if fertilized with ash constituents *plus* ammonium sulphate the yield

3 For example, one of Lawes' experiments gave the following yields of turnips:

No phosphate	2.2 tons per acre
Apatite	3.05 tons per acre
Apatite + H_2SO_4	6.8 tons per acre

4 Lawes describes the history of his discovery in his proof of evidence in an action for infringement of his patent for making superphosphate, 1853. He was not the first to publish experiments on the use of superphosphate, but he successfully upheld his patent, being apparently the first to use mineral phosphates for making superphosphate.

exceeded that obtained from farmyard manure (pl. 4A, opp. p. 12; fig. 1, p. 10).

These experiments gave the key to the puzzling discrepancy between Liebig's brilliant hypothesis and the stern realities of crop production. Lawes demonstrated the value to the plant of phosphates, and also of the

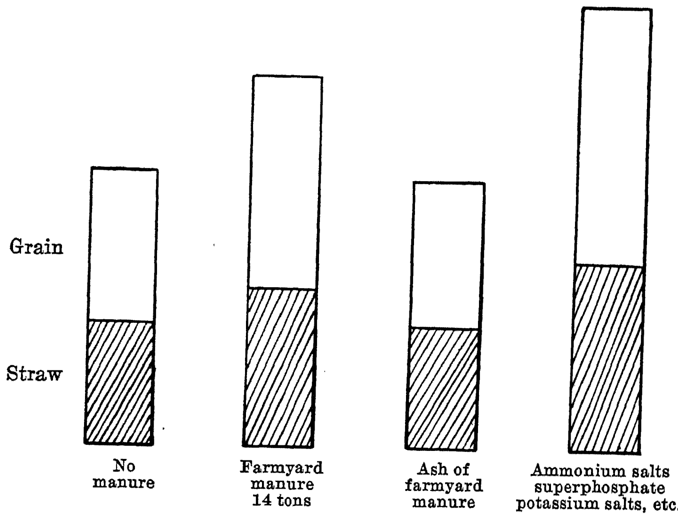


Fig. 1. Rothamsted, 1843.
Lawes' first experiments with wheat.

alkali salts on which Liebig had laid so much stress, but he showed clearly the mistake Liebig had made in leaving the nitrogeneous nutrients out of account. The famous Broadbalk experiment was continued year after year and afforded to a long succession of farmer visitors ocular proof of the fertilizing value of mineral constituents and nitrogen compounds (pl. 4A).

Lawes fully realized the commercial possibilities of his discoveries. At first he made the fertilizer mixture

or "patent manure" in the barn at Rothamsted (pl. 4B), but later he set up a factory at Deptford for manufacture on a large scale. Simultaneously he embarked on the extensive series of experiments in agricultural science now known all over the world as the Rothamsted experiments. He realized that this twofold set of activities would be beyond the power of one man to carry through, and at the outset (in 1843) he induced a young chemist, J. H. Gilbert (pl. 2), to join him.

The selection of Gilbert as his partner is remarkable evidence of Lawes' ability, so necessary in the successful execution of any enterprise, to choose his colleagues well. Lawes was a designer of great schemes; but he was less interested in filling in the details. Gilbert, on the other hand, had a magnificent aptitude for details but less power to emphasize the broad outlines. The distinction is well seen in their notebooks (pl. 5); Lawes' book contains the outline of the experiment clearly set out and the space where he meant to enter his observations, but there are only few records; while Gilbert's book contains such masses of figures that it is difficult to ascertain what the investigation was about. Each man supplied the deficiencies of the other and the two working together achieved results impossible for any one person working alone. They form the best example in the history of agricultural science of what is now known as team work. By 1855 they had so well justified science that British farmers subscribed to build a laboratory in which for the rest of their lives they worked (pl. 8A, opp. p. 20).

With the manufacturing and selling side of the business, Gilbert and Rothamsted had nothing whatever to do. Indeed, Lawes himself had to exercise some tact in the beginning; a gentleman in 1843 was hedged in with

many conventions. His first advertisement is couched in restrained, almost dignified language:

Gardener's Chronicle July 1st, 1843

GUANO ON SALE, as Imported, of first quality, and in any quantity, direct from the bonded stores, either in Liverpool or London. Also, NITRATE of SODA, Apply to H. ROUNTHWAITE & Co., Merchants, 6 Cable-street, Liverpool.

J. B. LAWES'S PATENT MANURES, composed of Super Phosphate of Lime, Phosphate of Ammonia, Silicate of Potass, &c., are now for sale at his Factory, Deptford-creek, London, price 4*s.* 6*d.* per bushel. These substances can be had separately; the Super Phosphate of Lime alone is recommended for fixing the Ammonia of Dung-heaps, Cesspools, Gas Liquor, &c. Price 4*s.* 6*d.* per bushel.

M'Intosh's New Edition of the PRACTICAL GARDENER, in ONE VOLUME, containing the latest and most approved modes of Management of KITCHEN, FRUIT, and FLOWER-GARDENS, GREEN-HOUSE, HOTHOUSE, CONSERVATORY, &c.; comprising numerous explana-

The first superphosphate was made from bone ash, that being the only source of calcium phosphate available at the time. Bones had always been in demand among the farmers and Lawes' discovery would not have added to the total amount of fertilizer obtainable had they remained the only source of phosphate. But Lawes' experimental proof that any other calcium phosphate would serve equally well was soon to find a remarkable application in practice. Almost immediately after the founding of the new industry the great deposits of mineral calcium phosphate began to be discovered, and Lawes was able to utilize effectively large quantities of phosphates which otherwise would have been unsuitable as fertilizer. He was a shrewd and highly capable business man; within twenty years 200,000 tons of superphosphate was produced annually and sold at the remunerative price of about £7 per ton. The use of nitrogenous fertilizers also increased. These developments gave farmers a means whereby they might manure all or any of their crops, and the increased level of production thus attained enabled England to feed her ever growing industrial population, an achievement which

PLATE 4A. The Broadbalk wheat field.

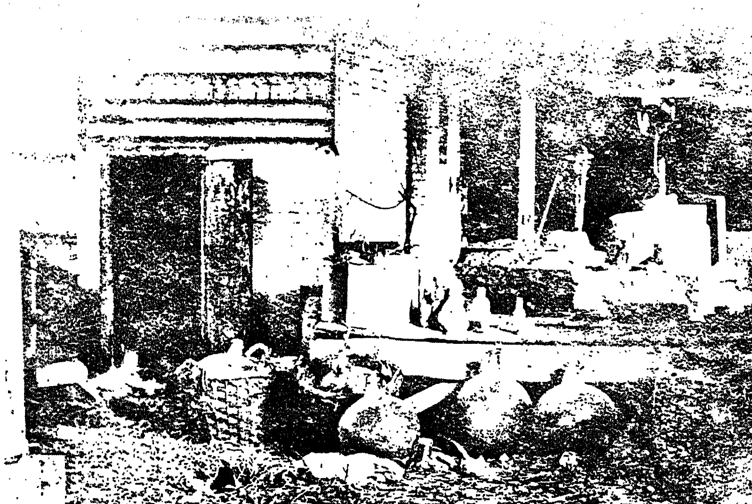


PLATE 4B. The barn at Rothamsted fitted as a laboratory and so used from 1842 to 1852.

would otherwise have been impossible. Similar results were obtained in the more densely populated countries of Europe. It is not too much to say that the discovery and develpment of artificial fertilizers has been one of the great factors in the making of modern Europe.

This was the first great triumph for chemistry in the realm of agriculture. But another was soon to come. The great importance of nitrogenous fertilizers was speedily recognized, but it was by no means clear that the visible supplies would last very long and thoughtful people began to be exercised for the future. This anxiety found expression in 1898, when the late Sir William Crookes, in his presidential address to the British Association at Bristol, startled that august assembly by declaring

> that England and all civilized nations stand in deadly peril of not having enough to eat. As mouths multiply, food resources dwindle. Land is a limited quantity and the land that will grow wheat is absolutely dependent on difficult and capricious natural phenomena. I am constrained to show that our wheat producing soil is totally unequal to the strain put upon it. The bread eaters of the world increase in geometrical proportion while the wheat area does not.

And then after elaborating this "colossal dilemma" he goes on to show the way out: the production of nitrogenous manures from the nitrogen of the air by electrical methods. Technical chemists took the matter up, and three kinds of processes are now in use: the union of nitrogen and oxygen in the arc, giving nitrates (pl. 6); the combination of calcium carbide and nitrogen to form calcium cyanamide which is subsequently converted into other compounds; and the union of hydrogen and nitrogen to form ammonia (Haber and Claude processes), which is then oxydized by the Ostwald process to nitric acid. These are well established in countries where water power is cheap, and already factories are erected near

waterfalls in America and Europe, despoiling the natural beauty after the manner of modern civilization (pl. 6). And although the first fruit of the new method was an intensification and prolongation of the great war, the benefit of an assured supply of nitrogenous fertilizers is great.

TABLE 4. WORLD PRODUCTION OF FERTILIZERS*
Million tons per annum†

	1913	1922
Raw phosphates	7.18	5.97
Superphosphate	11.3	8.84
Basic slag	4.41	2.80
Potassic salts	11.6	14.4
Nitrate of soda	2.77	1.06
Sulphate of ammonia	1.39	2.24
Synthetic nitrogen compounds	.26	.72

* From Production et consommation des engrais chimiques (Inst. Internat. d'Agr. Rome, 1924).

† The term ton as used throughout these lectures refers to the British ton, which is equivalent to 2240 lbs. The British bushel has a cubic content of 2218.192 cubic inches or 36.3460 liters. These figures are in contradistinction to the value of 2000 lbs for the American ton, and 2150.42 cubic inches, or 35.2361 liters, for the American bushel.

It is not my purpose to trace out the history of the artificial fertilizer industry: it is a wonderful story, and some of its episodes read almost like a romance. The quantities used by farmers in the countries of the civilized world are set out in table 4, which shows incidentally the effects of the war on fertilizer practice. The consumption of phosphates has perforce been reduced, especially in central Europe, because the major part of the raw phosphate comes from the United States and North Africa where depreciated currencies have but little purchasing power. How this fact will affect the nutritive

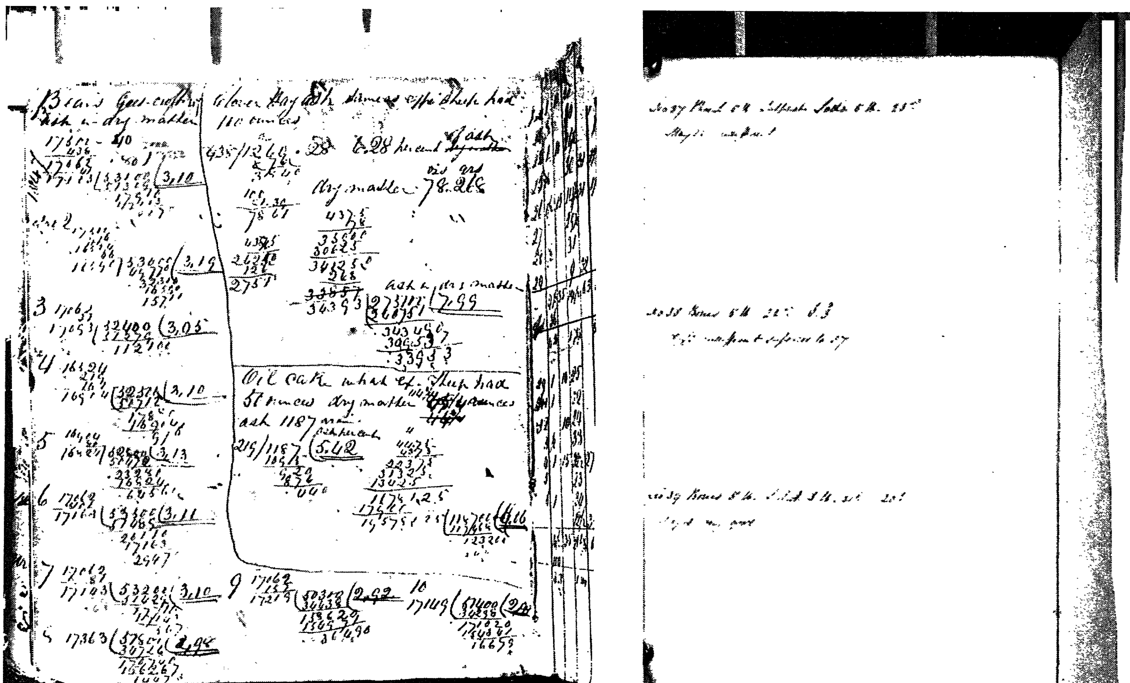


PLATE 5. Typical pages from the notebooks of (left) Joseph Henry Gilbert and (right) John Bennet Lawes.

value of the foods grown and, above all, how it will react on the health of the children remains to be seen. Consumption of nitrate of soda has gone down; again for currency reasons. As against this, consumption of sulphate of ammonia and of potash salts has gone up, the former being produced as a by-product in Britain and other European countries, and the latter being mined in France and Germany: all of these countries desire to sell their products.

TABLE 5. EFFECT OF SULPHATE OF AMMONIA ON CROP YIELD
INCREASES PRODUCED BY A DRESSING OF 1 CWT. PER ACRE
(British results.)

	Average of all soils and seasons	1922	1923	Average percentage of recovery of nitrogen
Wheat, grain (bushels)	4.5	3.25	....	39.0
straw (cwts.)	5.0	3.25	....	
Barley, grain (bushels)	6.5	5.5	4.5	47.5
straw (cwts.)	6.5	....	....	
Oats, grain (bushels)	7.0	....	8.3	46.5
straw (cwts.)	6.0	....	7.5	
Potatoes (cwts.)	20	22	22–25	50.0
Swedes (cwts.)	20	20	25	35.0

In academic science the handing over of a discovery to the technical workers marks the end of a story. In agricultural science, it simply opens a fresh chapter. As soon as farmers began to use artificial fertilizers a crop of difficulties arose which when examined by men of science were found to involve new problems of great scientific interest and technical importance.

Perhaps the most frequently occurring are in connection with the variation in effectiveness of the individual fertilizers with changes in soil and season. A fertilizer of great value in one season or on one farm may have no

action on another. In England variation is least in the case of the nitrogenous fertilizers, and the agricultural advisor is usually safe in predicting a return from them; the exceptional non-responsive soils having certain obvious characteristics which prevent his going astray. The increased crops represent less variation in recovery of the added nitrogen than might be expected, a fact

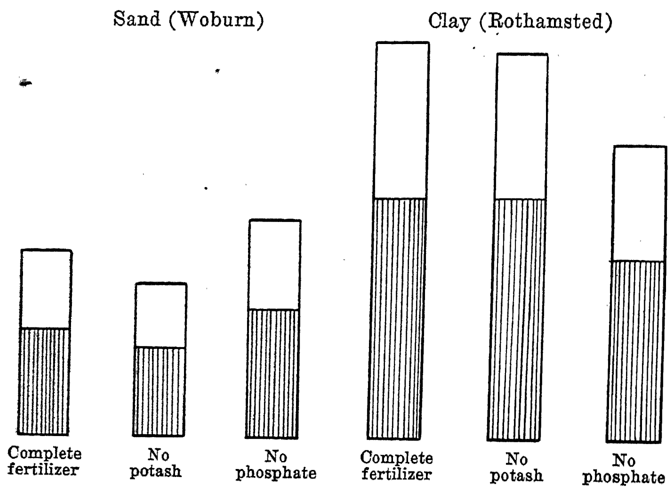
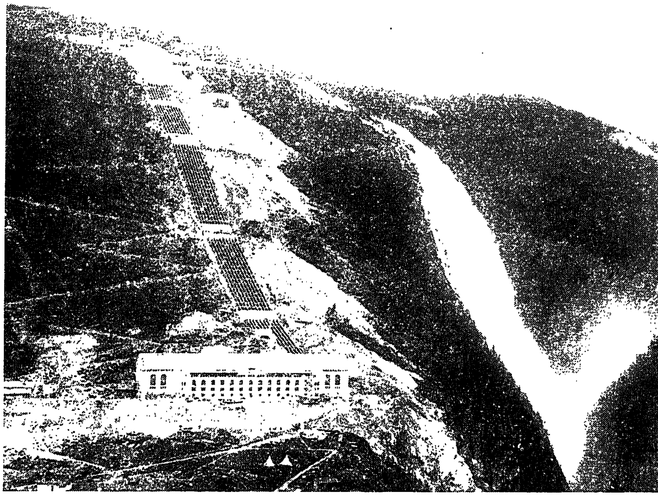


Fig. 2. Effect of phosphate manures on barley growing on sand and clay.

that offers much interesting material to the plant physiologist (table 5). Phosphates and potash, however, show considerable differences in action in different conditions (fig. 2). Phosphates nearly always lead to increased crops of swedes and turnips; they are necessary in small quantities for potatoes but may exert a depressing effect in larger dressings; they benefit cereals as a rule only on heavy soils and in cool or wet seasons; they have either no effect or a depressing effect on yields in sandy soils or in dry hot seasons. There is some evidence that phosphate



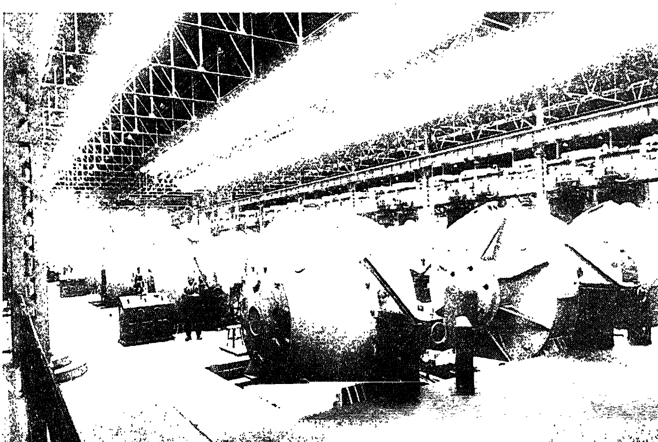


PLATE 6.

Upper: A factory on a fjord, Norway.
Lower: Nitrates produced from the air.

(Permission of the Nitrate Trading Co.)

nutrition is facilitated by soluble silicates. Potassic fertilizers usually increase the yields of mangolds and potatoes (table 6), and often increase those of leguminous crops, but not of other crops except on light sandy or chalky soils.

TABLE 6. EFFECT OF POTASSIC FERTILIZERS ON POTATOES. ROTHAMSTED

	Tons per acre		
	1921	1922	1923
Complete artificials—			
With farmyard manure	3.94	9.55	12.45
With no farmyard manure	3.76	8.30	12.25
Reduction by omitting potash—			
In presence of farmyard manure	0.31	1.52	0.79
With no farmyard manure	2.41	5.83	2.53

Two methods of exploring these facts have been adopted. It has been assumed that non-responsive soils are so rich in the particular nutrient that further additions are unnecessary. Soil analysis was therefore developed for the purpose of advising farmers whether or not they need add phosphatic or potassic manures. The so-called explanation is no explanation at all, but only another way of stating the obvious fact that no increase of crop has been obtained; nevertheless the diagnostic value of soil analysis is considerable. Its indications, however, break down altogether in the numerous cases where one and the same soil sometimes responds and sometimes does not respond to one and the same fertilizer for one and the same crop, as shown in figure 3, where are shown the effects of fertilizers on barley at Rothamsted for the years 1922 and 1923. Some seasonal factor is obviously operating, and the weather conditions of

1922 differed from those of 1923 in such a way as to make potassic fertilizers of more importance in the former year than in the latter. Another instance is afforded by the potatoes of table 6. It is abundantly proved that the soil, the climate, and the plant must be regarded as

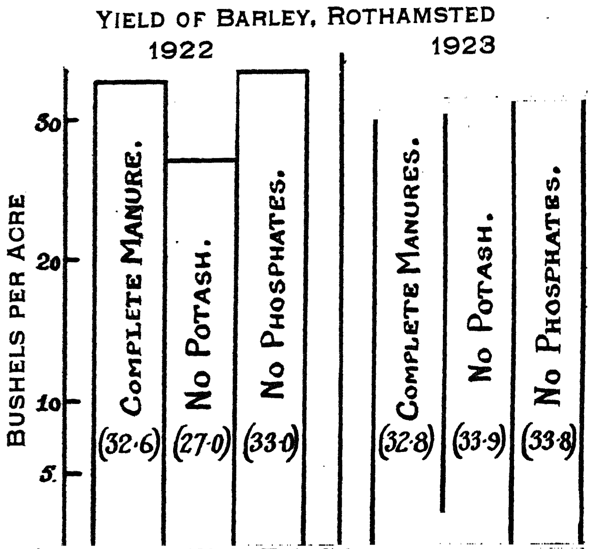


Fig. 3. Influence of season on the effectiveness of potassic and prosphatic fertilizers (Rothamsted barley).

a closely interlocking system and the effect of the fertilizer depends not only on the soil conditions but also on those of climate.

Recognition of this fact has led to the second method of studying the variations in the effect of fertilizers. It is found that fertilizers modify the habit of growth of the plant or its composition, and these changes modify the response of the crop to differences in its environmental conditions. Thus phosphatic fertilizers stimulate root development in the early stages of plant growth, an

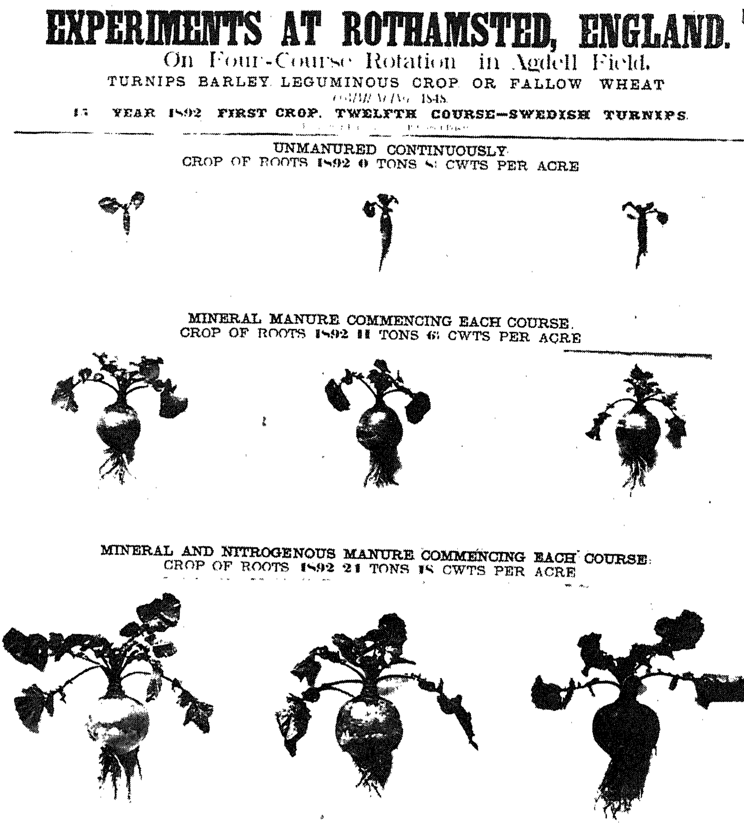


PLATE 7. Effect of phosphates on root development. Gilbert's chart drawn for his American lectures, 1893. Top row: unmanured. Middle row: superphosphate and potash. Bottom row: superphosphate, potash, and nitrogen.

effect of special importance to swedes and turnips (pl. 7); large quantities of superphosphates are annually used in Britain for the purpose of speeding up the early growth of these crops so that they may be hoed earlier in the season. Further, phosphates stimulate tillering of cereal crops (pl. 8B): both actions are advantageous to cereals on heavy soils. In the later stages of plant growth they hasten the maturation process (pl. 8C), a special advantage to cereals on clay soils or growing in cold, wet, late conditions. But these effects may be of no advantage to cereals growing on a sandy soil where the conditions are already favorable to root development, or in dry conditions where vegetative growth is already so restricted that any hastening of maturation may even diminish the yield (table 6). A similar paradoxial effect has been obtained by the addition of nitrogenous manures to tomatoes growing in borders (not in pots) under glass.[5] The nitrogenous fertilizer increased the leaf size and the stem but it did not increase the yield of fruit; on the contrary, it interfered with the 'setting' of the blossom and decreased the fruit yield. In pots a maximum effectiveness is reached beyond which further doses of nitrogenous fertilizer do not increase the growth (pl. 14A).

The effect of fertilizers on the composition of the plant is more easily demonstrated indirectly than by actual chemical examination. Middleton showed at Cockle Park that phosphates increase the feeding value of hay, so that one ton of hay grown with phosphate produced a greater live weight increase in sheep than one ton of hay grown without it. The result appears to be true of other fodder crops though the evidence is not

[5] W. F. Bewley, Cheshunt Experiment Station, Reports 1–7 (1914–1921).

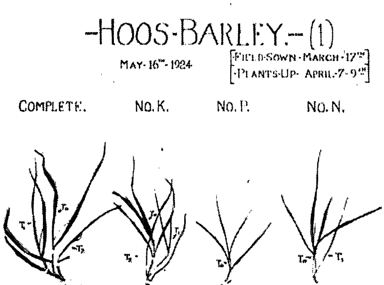
extensive. It is shown at Rothamsted[6] that potassic fertilizers improve the malting quality of barley, increasing the quantity of extract, the diastatic power, and improving its grade. Some of the consequences of these changes induced by fertilizers are far-reaching. The hastening of the maturation processes of barley by phosphates offers a method for obviating much of the destruction caused by the gout fly. The eggs of the gout fly are laid near the tip of the leaf of the young plant, and the larvae on emergence crawl downwards. If on their way they find the embryonic seed head they enter and devour it: if the phosphates have caused the head to emerge from the ensheathing leaves the plant escapes injury. Bewley has shown that potassic fertilizers increase the resistance or decrease the suitability of the tomato plant to the Bacterial Stripe disease (*Bact. lathyri*). E. A. Andrews in India has made a like observation in regard to tea bushes: these when treated with potassic fertilizers escape attack from the mosquito bug (*Helopeltis*) for the rest of the season. Davidson has shown that it is possible to alter the suitability of the bean plant to the serious *Aphis* pest.

The effect of nutrients on the plant depends not only on the factors already discussed; the nature and quantity of the nutrient, the soil and the climate; it is also influenced by the period of growth in which the nutrient is presented to the plant. Nitrogenous fertilizers show marked differences in effect according as they are given early or late, while Gericke has recently obtained remarkable increases in growth of wheat, by supplying phosphate only in the early stages of growth, and withholding it later on.

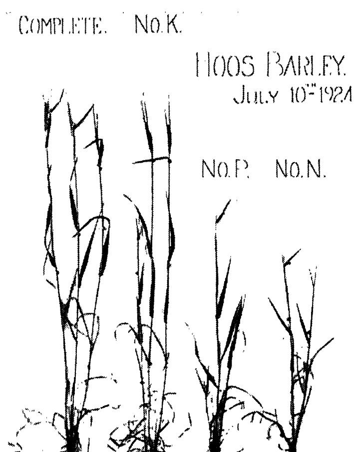
[6] Barley research scheme of the Institute of Brewing, Jour. Inst. Brew., 1924, vol. 30, p. 969.

Plate 8a. The Rothamsted laboratory in which Lawes and Gilbert worked. Demolished in 1914 because of its unsafe condition.

Barley at Rothamsted.



8b



8c

Effect of fertilizers on the tillering and maturation of cereals. 8b, early growth; 8c, later growth.

Another group of investigations arises out of the fact that plant nutrients cannot be added alone; they are always in combination with other things. The nitrogen is in practice given as ammonium sulphate or as sodium nitrate; the potassium is supplied as potassium sulphate or potassium chloride, while the phosphorus is supplied as calcium phosphate: these other constituents have actions on the soil and on the plant which may be of considerable practical importance. The first of these indirect actions to be studied was that of ammonium sulphate. Wheeler[7] had been using this substance in Rhode Island and observed that on certain soils it greatly injured the crops; the trouble was traced to the development of acidity in the soil and was remedied by the application of dressings of lime. The observation led direct to the interesting and suggestive work which has since been carried on by Hartwell and Pember at the Rhode Island Station. A few years later the same phenomenon was observed by J. A. Voelcker[8] at the Woburn Experimental Farm. The ammonium sulphate had been used year after year on the same land for twenty-five years for the manuring of wheat and of barley; the yield of barley was maintained for many years but suddenly collapsed and the crop now fails regularly (pl. 9). Wheat continued to grow for a longer period but is now showing signs of failure. The effects of this long application of ammonium sulphate are mitigated by dressings of potassium sulphate and superphosphate, and as at Rhode Island they are completely remedied by dressings of lime. The phenomena have not been sufficiently investigated to allow adequate discussion of the factors in operation.

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[7] Wheeler, H. J., Rhode Island Exp. Station, Third Annual Report, 1891, p. 53; also later Reports.

[8] Jour. Roy. Agr. Soc., 1897, p. 287, and later years.

Ammonium sulphate reacts with the calcium carbonate in the soil and converts it into calcium sulphate, which has no power of neutralizing any soil acids that might accumulate. But the effect seems something more drastic than this. Hall supposed that the ammonium sulphate is decomposed in the soil by fungi which assimilate the ammonia, leaving free sulphuric acid. This view fits the facts better than the other, but it is by no means definitely established and it opens up interesting possibilities for investigation.

Sodium nitrate when used continuously on heavy soils tends to injure their texture. Several explanations have been suggested; the sodium nitrate may react with the calcium carbonate to form calcium nitrate and sodium carbonate which deflocculates the clay; or there may be decomposition at the plant root, the nitrate radicle being absorbed and the sodium left behind, becoming converted into carbonate or bicarbonate which, as before, deflocculates the clay. The simplest and most far-reaching explanation is that of Gedroiz, which will be discussed more fully in the final lecture.

A more recent problem is presented by the necessity imposed on farmers by their economic condition of using the cheapest fertilizer that will give the desired result. Both the sulphates and the chlorides of potassium and ammonium are available to the farmer, and the chloride is the cheaper per unit of potassium and of nitrogen. On purely physiological grounds one would suppose that the chloride would be somewhat harmful while the sulphate would not, and that therefore the sulphate should be the better fertilizer. This result has been obtained in field trials. But the opposite result has also been obtained and chlorides have proved more effective as fertilizers than the sulphate. The results of

PLATE 9. Barley plots at Woburn: the one to the right is acid and fails to carry barley; to the left, lime has been added and a good crop obtained.

numerous British trials supervised from Rothamsted are set out as a distribution curve in figure 4. The chief factor causing the difference appears to be the rainfall; under low rainfall the chloride is less effective than the sulphate, under high rainfall it is more so. There appears also to be a soil factor; the chloride tending to be less useful than the sulphate on sands but equally or more

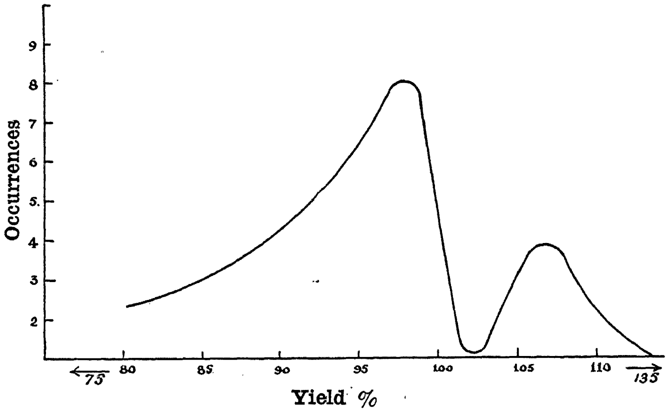

Fig. 4. Yields from ammonium chloride when that from equivalent amount of ammonium sulphate equals 100. All British centers 1923.

useful on clays. It is very difficult to explain these results; they are being studied at Rothamsted jointly by an agriculturist, a plant physiologist, and an ecologist, Mr. H. V. Garner, Dr. E. J. Maskell, and Mr. T. Eden. The question is of great practical importance in Europe, involving much bigger issues than are usually associated with fertilizer problems. Potassium chloride is obtained from Alsace; it is a French product. Potassium sulphate is obtained from Stassfurt and is a German product. The expert must ascertain the fertilizing properties with the utmost care so that farmers may have full information before making their choice.

As between ammonium chloride and ammonium sulphate the problem is no less urgent. For reasons which need not be discussed it is imperative to establish the fixation of nitrogen on a large manufacturing scale in England. In peace time the product would be used as fertilizer: it might be either ammonium chloride or ammonium sulphate, but the decision must be made before the industry can be fully set up.

A final group of problems arises from the possibility that other nutrients may be important besides the nitrogen, potassium, and phosphorus of the conventional fertilizer practice. Plant physiologists have shown that several others are essential, which may not always be present in sufficient quantities in the soil. It was found long ago at Rothamsted that soluble silicates increase the yield of barley when supplies of phosphate are restricted: this result is now being studied in Germany to see if the home-produced silicates can eke out the restricted supplies of imported phosphate. W. W. Garner and his colleagues[9] studied a curious physiological disease of tobacco, a chlorosis known as "Sanddrown" and traced it to insufficiency of magnesium in the soil: the trouble was remedied by small dressings of magnesium sulphate. This same salt has produced beneficial effect on potatoes in some of the Durham trials.

Probably the most dramatic effects, however, are those produced by minute quantities of certain elements, iron, boron, manganese, and a few others, on the growth of plants supplied with a complete nutrient solution. Small quantities of manganese were found by Bertrand to be essential to plant growth. Boron is being studied at Rothamsted, the investigation having origi-

[9] Garner, W. W., McMurtrey, J. E., Bacon, C. W., and Moss, E. G., Jour. Agr. Res., vol. 23, pp. 27–40 (1923).

PLATE 10. Influence of boric acid on the development of the broad bean in culture solution.

Each set received a complete solution; that to the right has nothing else. The others from right to left received boric acid in amounts corresponding respectively to 1:500,000; 1:100,000; 1:50,000; and the extreme left, 1:5,000 H_3BO_3. (K. Warington), Annals Botany, vol. 37, pp. 1–44, 1923.)

nated in an observation made when the entomologists were adding various poisons, including borax, to soil in which broad beans were growing, in the hope of making the plant unsuitable to the *Aphis*. Borax markedly increased the plant growth, and when the botanical staff took the matter up they found that the old 'complete' nutrient solution would not allow beans to develop unless a trace of borax was supplied (pl. 10). Mazé of the Institut Pasteur, Paris, has added other elements, iodine, zinc, aluminium, etc., to this remarkable list. The subject is under investigation by Dr. C. B. Lipman. The analogy with vitamins is obvious, but analogy is the most treacherous method in science.[10]

We may now look back over the whole of the material I have presented. We have seen how in the beginning of the inquiry into plant nutrition a few well-planned experiments by van Helmont and by Woodward gave a considerable amount of information and afforded a simple and apparently complete explanation of the whole phenomena. This was followed by a great deal of work of varying character and quality that brought out many new facts or supposed facts, but, so far from clearing up the problem, only confused what had seemed to be a simple matter. From this apparently hopeless tangle of complexity, the brilliant chemist, Liebig, drew out a simple generalization, which, when modified and expanded by the experimental genius of Boussingault, Lawes, and Gilbert, was found by experience to be trustworthy and therefore was adjudged to be a close approximation to the truth. The practical application came suddenly and unexpectedly.

10 Experience has not borne out the high value placed on analogy by the earlier workers. Priestley (History of Electricity, 1767) has said: "Analogy is our best guide in all philosophical investigations; and all discoveries, which were not made by mere accident, have been made by the help of it."

This however by no means ended the story. Practical application on the large scale revealed difficulties and inconsistencies which farmers could not explain and which therefore have been sent in to the agricultural advisors. Many of the phenomena are inexplicable on present knowledge. It appears therefore that the simple generalization is only a first approximation to the truth. The whole problem is now back again in the laboratories for reinvestigation to obtain if possible a closer approximation to the truth. We shall find this to be the usual course of events. The first workers obtain much knowledge rapidly; then comes a period when progress apparently ceases and confusion reigns instead. Suddenly the generalization appears and sooner or later thereafter the practical application. Then comes the large-scale test, the criticisms, and the curious and inexplicable observations of the practical grower. And although we who are working in the experimental stations may sometimes be tempted to feel that these observations, being unknown to us, cannot possibly be true, nevertheless they often are true and contain the germ of highly interesting scientific problems, sometimes indeed the key to further progress. We shall see in later lectures how history is repeating itself in other branches of the science. But progress is always slow, and we can never see the whole of anything in Nature; as Browning said, we explore with a taper and not with a torch.

> 'Tis man's to explore
> Up and down, inch by inch, with the taper his reason;
> No torch, it suffices—held deftly and straight,
> Eyes, purblind at first, feel their way in due season.

Chapter II

POSITIVE SCIENCE AND EXACT DEMONSTRATION

No scientific investigation is complete until its results can be expressed quantitatively. Only when this is done can the investigators feel reasonably certain that they have gained the right perspective and that they know how nearly their hypotheses approximate to the truth. The perfect fit is never obtained, for there is always something more in every scientific problem than any human being can get out of it. But even the poets have recognized the value of exact measurements as the nearest expression mankind can obtain of the great facts of Nature. Walt Whitman says:

> I accept reality and dare not question it.
> Hurrah for positive science! Long live exact demonstration!
> Fetch stonecrop mixt with cedar and branches of lilac.
>
> . . . .
>
> This is the geologist, this works with the scalpel, and this is a mathematician.
> Gentlemen, to you the first honours always.

For many years investigators have been trying to give mathematical expression to the facts of plant nutrition and although the result is a mass of formulae and curves unattractive to the general reader it must always be remembered, as D'Arcy Thompson has said, that when science begins to speak plainly she speaks the language of mathematics. It must be admitted that as yet no success has been obtained commensurate with the efforts involved in either composing or reading the published papers, nevertheless the more recent attempts offer much

promise for the future. The problem has been attacked in two ways. Curves have been set up in the manner usual in pure science and these have been expressed by equations. The first attempt was by Liebig, who argued that plant growth is proportional to the supply of the nutrient present in minimum amount; the relationship between growth and nutrient is therefore a straight line. Lawes and Gilbert modified this by showing a falling off in response when the fertilizer exceeded a certain amount and thus gave the earliest demonstration of the operation of the Law of Diminishing Returns in fertilizer practice (pl. 11A).

F. F. Blackman's idea of Limiting Factors may be used to explain the falling off: the response of the crop to further increments of the factor is limited by the insufficiency of some other factor, further increases in which would allow the proper proportional rate of growth to be resumed. This is a simple mode of expression and is very helpful in discussing those problems in soil fertility in which one factor is exerting a dominating influence, and may therefore be regarded as the chief limiting factor. It often happens, however, that increases in any of the factors, even those apparently present in ample quantity, lead to further growth, and in this sense every factor may be described as limiting except only in the extreme cases where it is harmful.

Liebig's simple proportional relationship does not fully fit the facts of plant growth, though it is possibly more nearly correct for the absorption of plant nutrients, and attempts have been made to find a closer approximation. The most important of these is by E. A. Mitscherlich, whose views are developed in the latest edition[1] of his Bodenkunde, one of the most interesting

[1]Ed. 4, 1923.

recent books on soil. His basic assumption is as follows: The increased yield produced by increments of a nutrient is proportional to the decrement below the maximum producible if the nutrient were present in excess. In

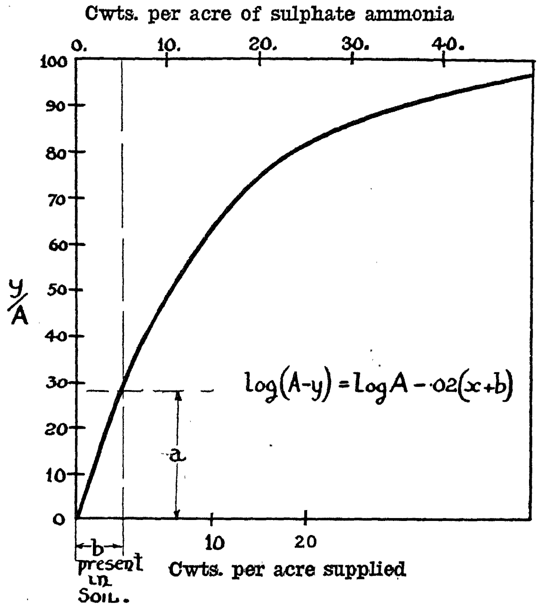

Fig 5. Mitscherlich's curve showing the amount of growth as percentage of the maximum y/A when sulphate of ammonia is used as the source of nitrogen. All experimental points should lie on this curve.

this form the statement is expressible, not by a straight line, as in Liebig's form, but by a logarithmic curve (fig. 5), the equation for which is:

$$\frac{dy}{dx} = k\ (A - y)$$

or $$\log_e (A - y) = \log_e (A - a) - cx$$

which may also be written

$$\log_e (A - y) = \log_e A - c(x + b)$$

where x = the amount of factor added,

b = amount of factor present before addition,

y = the amount of growth (i.e., yield *less* weight of seed) obtained by application of amount x of factor,

A = the maximum amount of growth possible when factor is no longer setting a limit,

a = yield without addition of factor,

c = a constant.

Mitscherlich asserts that c is a constant characteristic for each manure and is the same for all crops and soils; he calls it the "Wirkungsfaktor." The values given to the constant are:

	Doppel zentners per hectare	Cwts. per acre
Sulphate of ammonia	0.025	0.020
Nitrate of soda	0.02	0.016
Superphosphate	0.08	0.064
40% potash salts	0.13	0.010

If these values really were constant, an experimenter could, by means of a single field trial, predict the yields obtainable from any given quantities of the fertilizer, a result which would be of enormous practical importance.

This work has led to an extended controversy, perhaps the most voluminous in the literature of agricultural science, the other protagonists including Baule, Frohlich, Meyer, Pfeiffer, and Rodenwald.

Three serious criticisms have been brought forward. The first is one of principle: the formula assumes that the plant receiving a large dressing of nutrient is essentially the same as one receiving small dressings so that the subtraction of weights implied in the term $(A - a)$ may logically be performed. Actually this is not altogether

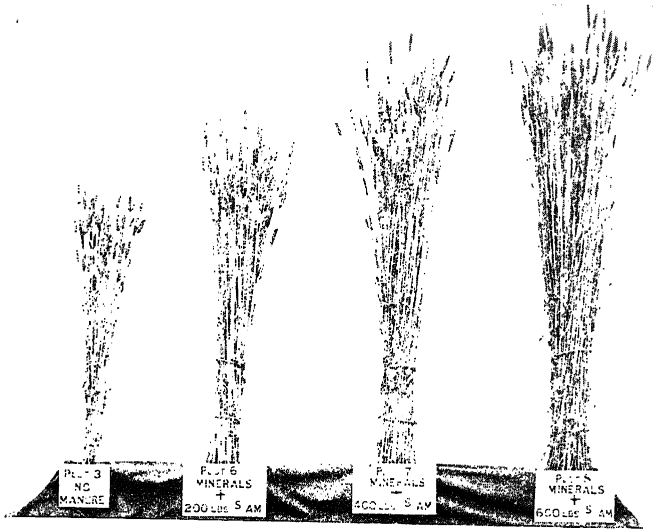

PLATE 11A. Lawes and Gilbert experiment. Increase in wheat crop yield with increasing supply of nitrogenous fertilizer. The left hand sheaf has no nitrogenous fertilizer, the others have amounts increasing to 600 lb. per acre of ammonium salts, the quantity given to the plot from which the right hand sheaf is taken.

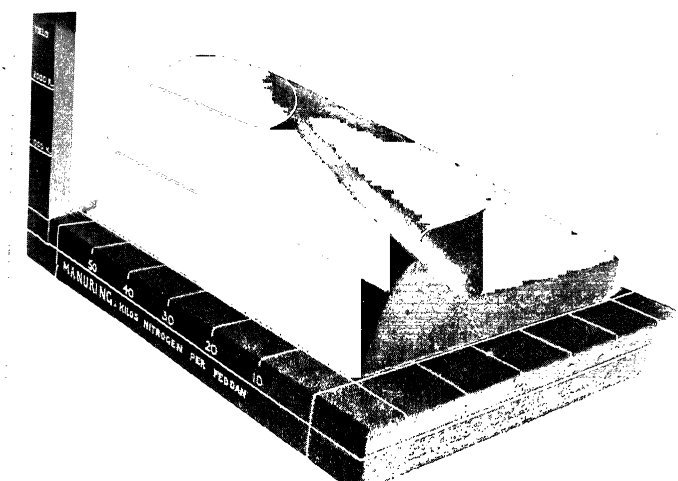

PLATE 11B. J. A. Prescott's surface: expressing the growth of maize with varying spacing and nitrogen supply. Data in Sultanic Agr. Soc., Bull. 4 (1920).

true: the nutrient not only increases the plant but changes it to some extent.

The second objection is that no definite maximum corresponding with A exists in reality: the amount of growth depends not only upon the factor under investigation but upon all others concerned in the process. This difficulty is recognized by Mitscherlich and has been studied by Baule, who supposes that the yield is determined by the product of the expressions for each of the factors involved. He transcribes Mitscherlich's equation into its other form,

$$\frac{y}{A} = 1 - e^{-cx}$$

and then expresses the yield thus:

$$\text{Yield} = A\,(1 - e^{-c_1 x_1})\ (1 - e^{-c_2 x_2})\ (1 - e^{-c_3 x_3})\ (\quad)\ \text{etc.}$$

Three things are implied in this expression:

(1) The yield, and the increments of the yield, are determined by all the factors concerned in plant growth.

(2) The percentage increase in yield brought about by increments in manures or other factors is a constant for the manure and is independent of all other factors (table 7, p. 60; and fig. 6).

(3) The efficiency of a plant food or other factor is completely defined by the "Wirkungsmenge"

$$h, \text{ which} = \frac{\log_e 2}{c} = \frac{0.7}{c}$$

where c = Mitscherlich's "Wirkungsfaktor."[2]

[2] The "Wirkungsmenge" is defined as the amount of the factor needed to give one-half of the maximum yield obtainable by increasing the factor, all others remaining constant; i.e.,

$$h = x \text{ when } x \text{ is such that } y = \tfrac{1}{2}A$$
$$1 - e^{-ch} \text{ then becomes } = \tfrac{1}{2}$$
$$\text{and } h = \frac{\log_e 2}{c} = \frac{0.7}{c}$$

The third objection is that constant values cannot in fact be obtained and some selection always has to be made to obtain A: this would in any case be objectionable but it is especially so for this particular quantity. So long as the experiments were confined to sand cultures the selection does not usually put too great a strain

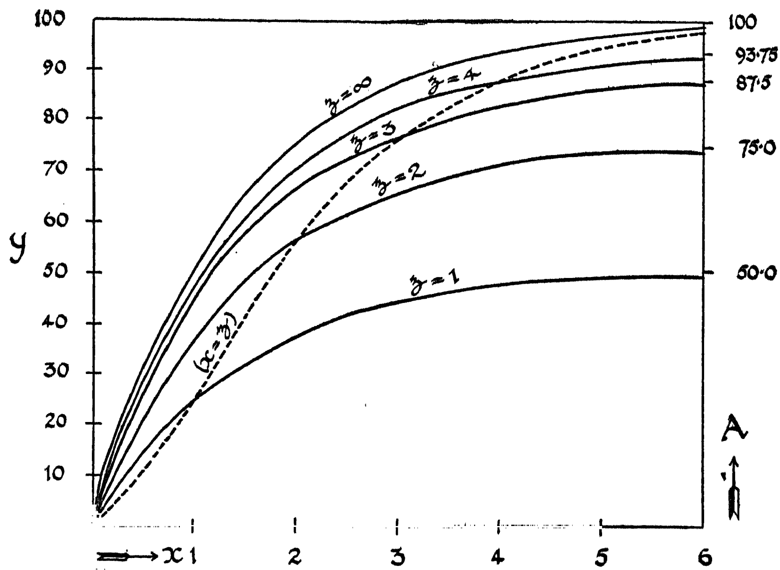

Fig. 6. Baule's curves showing amount of growth y, as percentage of the maximum possible when two factors x and y both vary. When $x = z$ the curve (shown by dots) becomes sigmoid.

on the reader, but in the field experiments Mitscherlich completely shocks us by assuming a value for x (the fertilizer added) that will fit the results yet differs materially from the quantity of the fertilizer actually added. He justifies this procedure by assuming that the difference represents the amount present in the soil and available to the crop, and he regards the process not only as a proof of the validity of the equation but as a

means for calculating the amount of 'available' plant food in the soil.

Naturally, men of science object to the method. But we must not let the defects blind us to the valuable possibilities of the work. Further developments will no doubt lead to the rejection of the useless parts, but, in Mitscherlich's own phrase, when we are emptying the bath we must be careful not to pour out the baby.

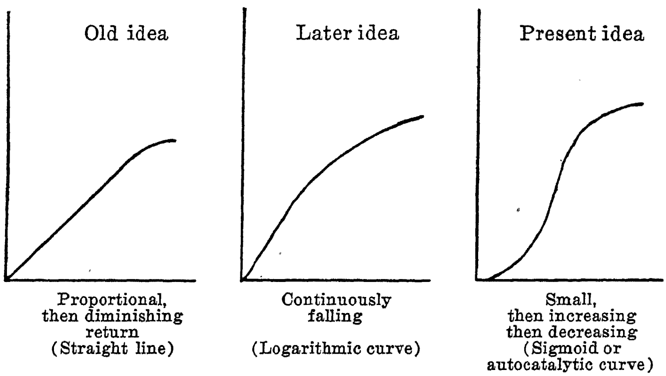

Fig. 7. The three types of curve showing the effect of fertilizer on crop yield.

The generalized form of the expression may give curves which are almost linear, or logarithmic, or sigmoid in type, and the field results actually fall into these groups (fig. 7).

Many more experimental data must be accumulated before the problem is solved. Meanwhile the results are best expressed by experimental curves, or, where two variables are studied, by a surface, as has been done by J. A. Prescott (pl. 11B).

The second method of attempting to give quantitative expression to the facts of plant nutrition and growth is being developed at Rothamsted in the new statistical

department under R. A. Fisher. It is an adaptation of the mathematical methods which have enabled statisticians to study population problems with great success, and it has the advantage that it takes into account all the factors operating in the field. Given sufficient data it is possible by these special methods to disentangle the effects of the various factors and so to state the field problem in terms of a number of single factor problems of the kind with which the ordinary scientific worker is

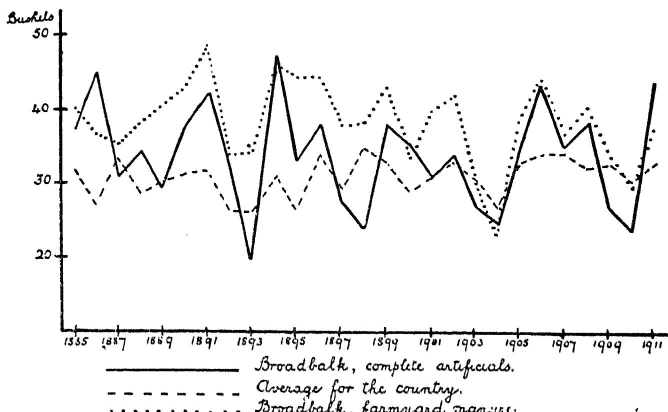

Fig. 8. Yields of wheat from Broadbalk plots manured with complete artificial manures, and farmyard manure, respectively, compared with average yield for the whole county.

familiar. The first set of data to be investigated[3] by this method were those of the famous Broadbalk field on which wheat has been grown for eighty-one years continuously; the treatment has not varied for seventy-three years, and during the whole of this time there have been but few changes in the staff so that the methods have not greatly altered. The records have been most carefully kept and they now constitute a prodigious mass of data before which the ordinary person quails but in which

[3] Jour. Agr. Sci. vol. 11, p. 107 (1921).

the statistician revels. The yields on the different plots vary greatly from year to year not only absolutely but also relatively. Analysis shows that three sets of factors influence the variation: one, that operates continuously and progressively, always in the same direction, making for a steady falling off in yield; a second, that operates

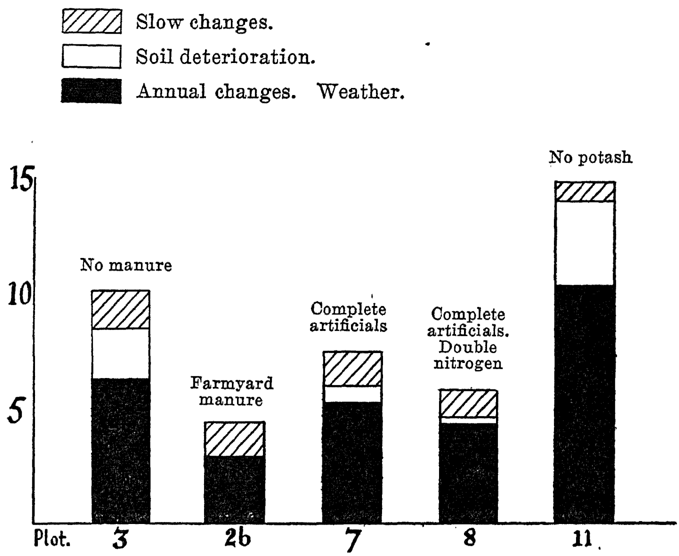

Fig. 9. Variation in wheat yields, bushels per acre. Broadbalk. R. A. Fisher.

progressively, but sometimes in one direction and sometimes in the opposite; and a third, that operates erratically. The statistician gives quantitative expression to these factors and shows their respective influence on the yields, but he cannot identify them. It may safely be assumed that the progressively harmful factor is soil deterioration; the factor which is progressive for short periods only is provisionally supposed to be weed infestation; while the erratic factor is easily identified by any

Britisher with the weather, which varies discontinuously and apparently independently of the preceding season.

The results (figs. 8, 9) show that the variation is far less on the plot receiving farmyard manure than on any of the others; it is greatest on the incompletely manured plots. The continuous progressive factor identified with soil deterioration occurs on all plots even those receiving complete artificial manures, though it is least where the dressings are heaviest; but it hardly shows on the plots receiving farmyard manure; it is, however, very marked on plots receiving incomplete dressings: thus the omission of potash has a serious effect even on the heavy Rothamsted soil, which is supposed to be well supplied with this constituent. The disturbing effect of weather is least marked on the plot receiving farmyard manure, and greatest on the plot receiving incomplete artificials.

The data on the Broadbalk field have been further analyzed to determine the effect of rainfall.[4] It is ancient knowledge that this differs according to the period of growth, being under European conditions more harmful in winter than in summer.[5] But mathematical expression can now be given to this effect on the Broadbalk field and the influence on crop yield of one inch of rain above the normal in any month can be predicted (fig. 10).

A similar investigation has been made of the Hoos field[6] barley yields, this crop, like the wheat, having been

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[4] Phil. Trans., vol. 213, pp. 81–142 (1924).

[5] Recorded in Virgil's Georgics, Book I, lines 100–103:

"Umida solstitia atque hiemes orate serenas,
Agricolae: hiberno laetissima pulvere farra.
Laetus ager: nullo tantum se Mysia cultu,
Jactat et ipsa mirantur Gargara messes."

"Farmers! Pray for wet summers and fine winters! From winter's dust comes great joy to the corn, joy to the land. By no tillage can Mysia have such cause for excitement or Gargarus for marveling at his own crops."

[6] Jour. Agr. Sci., vol. 16, p. 434 (1924).

PLATE 12. The mangold experimental field at Rothamsted. Plots on the right received farmyard manure and artificial manures; those on the left artificial manures only. In spite of the abundance of nutrients these latter have made little growth because of the lack of moisture. Later in the season, after rain has fallen, the difference tends to disappear.

grown continuously and on the same land for seventy-three years. Further data to be examined when time permits are those obtained on the lighter, more sandy soil at Woburn, where wheat and barley have been grown continuously for fifty-two years. We hope it may be possible after an examination of these and other records

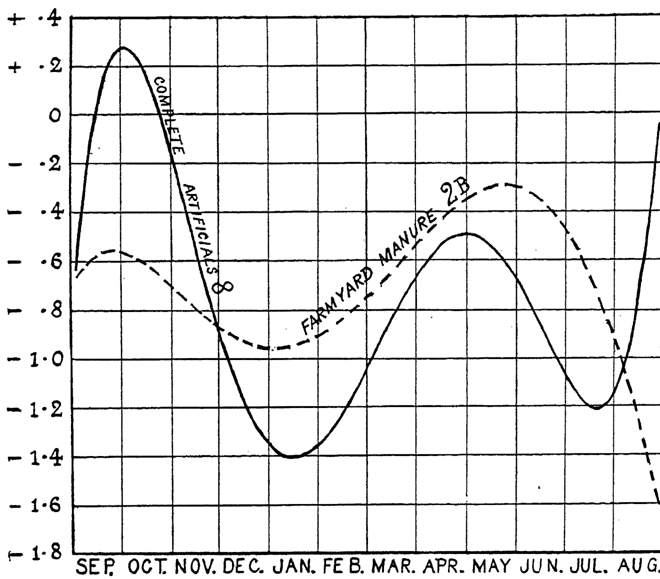


Fig. 10. Average effect in bushels per acre of one additional inch of rain (Broadbalk wheat). All effects below line 0 are depressions in yield.

to construct tables showing the expectancy of crop yield, corresponding with the tables showing the expectancy of life. If this could be done it would become possible for the county agent to advise farmers in terms of definite odds what would be their prospects of success with a given fertilizer mixture. It is not at all impossible that agricultural experts may be able at some future time to use some such form as the following:

.... Farm.

Soil Above or below average for type	per cent.	Weather. Above or below average Rain		Temp[r].	etc
Sand	......	1st Month	.....	......	......
Silt	......	2nd "	.....	......	......
Clay	......	3rd "	.....	......	......

In above conditions the chances are ...... to 1 that the following mixture will increase the yield by ...... bushels:-

The farmer would understand the language and could decide whether or not to take the risk. But even more important would be the fact that the risk, being definitely ascertained, could be covered by insurance. At present crop yields are uninsurable in England at any reasonable premium; if, however, there existed trustworthy tables of expectancy of crop yield, crop insurance would become as readily amenable to business management as life insurance. This is not of course expected to follow at once—the details of life insurance took nearly one hundred years to develop and crop insurance may take as long.

The statistical treatment has emphasized the fact that farmyard manure behaves differently from artificial manures and is not in fact wholly replaceable by them. This conclusion has already been reached by agricultural chemists after a long and very interesting controversy. In Lawes and Gilbert's first experiments the complete artificial manures had actually given larger yields of wheat and barley than had farmyard manure and although Lawes and Gilbert themselves did not urge that artificials were therefore better than farmyard manure,

some of their disciples did so, going futher than the masters, after the manner of disciples. The great French agricultural chemist, Ville, went so far as to assert that farmyard manure was unnecessary and could in practice be economically replaced by artificial manures.

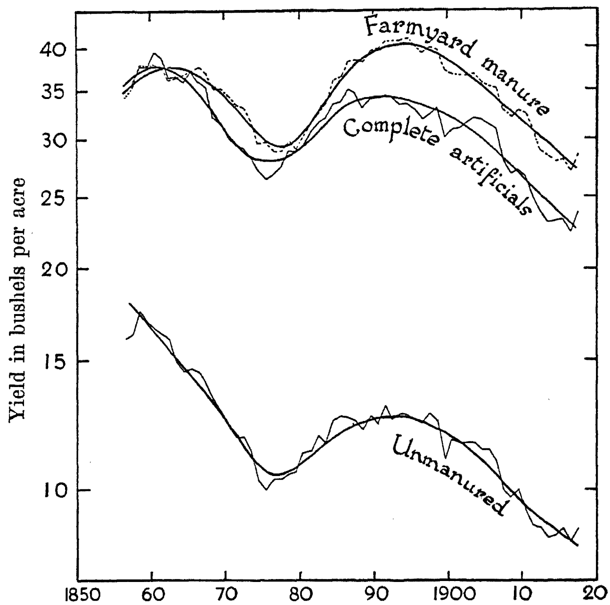


Fig. 11. Yields of wheat, 10-year means 1852–1922, Broadbalk field, Rothamsted.

Practical men in Great Britain never accepted this view but maintained that farmyard manure was more effective than artificial fertilizers and they came in for some abuse for their supposed prejudice against new ideas and scientific discoveries. For a long time this was supposed to be the line of cleavage between science and practice, and even as recently as seventeen years ago, when I first went lecturing among farmers, the older members of my audiences always assumed that I should

disparage farmyard manure and set up the thesis that artificial manures were the right and proper things to use. Fortunately for agricultural science, Gilbert was a

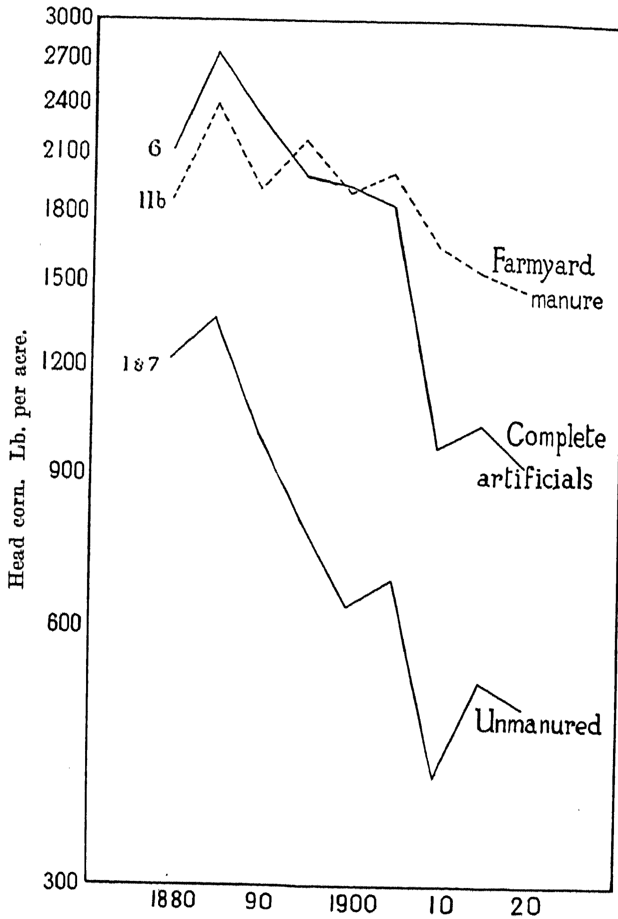


Fig. 12. Woburn, yields of continuous barley, 1877–1922.

strong-minded man with a great love of twenty-year averages, and accordingly he persuaded Lawes to continue the Rothamsted field experiments long after they

might otherwise have been discontinued. It then appeared that the superiority of artificials to farmyard manure was not permanent. For the first few years the artificials considerably enhanced the fertility of the soil, but after a time their effect began to fall off. Farmyard manure, on the other hand, showed a smaller falling off,

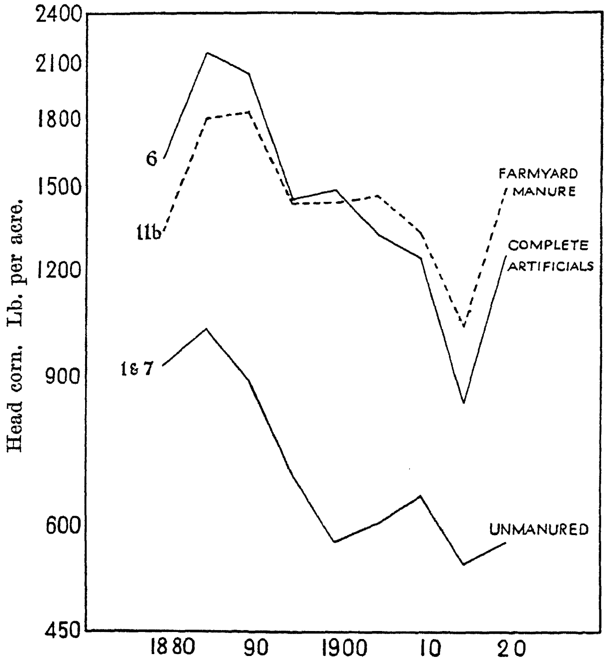


Fig. 13. Woburn, yields of continuous wheat, 1877–1922.

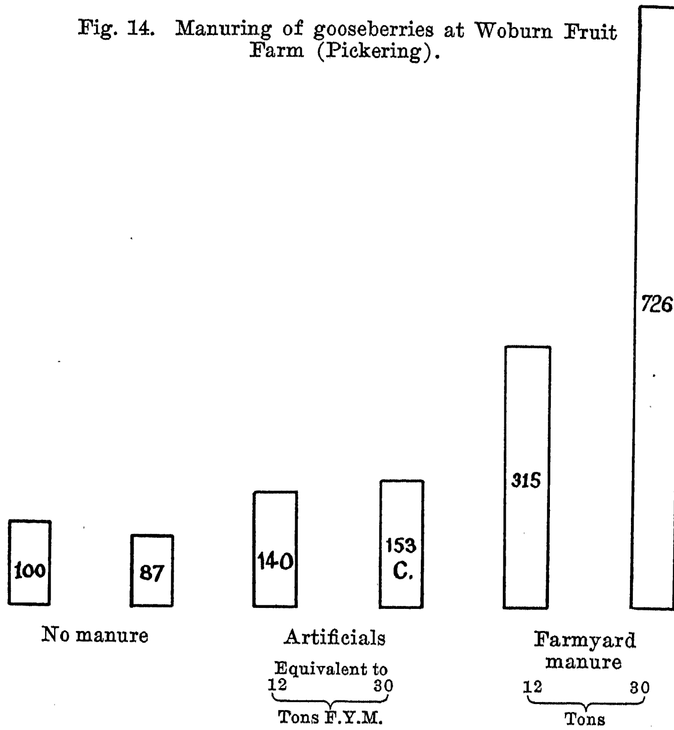
and though, both at Rothamsted and Woburn, it began by being less effective than artificials it was finally more effective: the difference has now become rather marked figs. 11, 12, 13).

A second respect in which farmyard manure differs from artificial manure is that, as already pointed out,

crops receiving it are less liable to suffer from seasonal factors than those receiving artificials only, so that the fluctuations in yield from season to season are least marked on the farmyard-manured plot (fig. 8).

A third effect has recently been brought out, though it has not yet been much studied. Some crops seem to

Fig. 14. Manuring of gooseberries at Woburn Fruit Farm (Pickering).



respond markedly to farmyard manure. Clover, one of the most important crops in Great Britain, is an example: it responds better to farmyard manure than to any combination of artificials yet tested, giving not only a better yield of clover hay but also enriching the ground and so improving the succeeding crop. Gooseberries were

shown by Pickering at the Woburn Fruit Farm to respond better to farmyard manure than to artificials (fig. 14) and a similar result is shown by citrus fruits at Riverside, California. These and other experiments prove that farmyard manure has important effects on plant growth which are not produced by artificial manures. The conclusion applies to humid climates, though not, apparently to unirrigated crops in arid conditions.

When a conclusion of such practical importance is reacted, it is wise to split the subsequent investigation into two parts: (1) the purely scientific study of the phenomena so as to discover the facts and elucidate the principles involved; (2) an agronomic investigation, the object of which is to show the farmer how to utilize the knowledge so far gained but without attempting to explain or even understand the facts. In this particular instance the purpose of the agronomic investigation is to show farmers how to increase their supplies of farmyard manure either by increased production or diminished wastage, or to find other substances that may be used instead, such as green manures, residues of grass and clover crops, etc. The four branches of the agronomic investigation are as follows:

1. The best ways of making, storing, and using farmyard manure.
2. The use of organic substances, such as shoddy, oil cake residues, sewage sludge.
3. The designing of a rotation in which the organic matter of the soil becomes increased: e.g., by lengthening the period in grass; by introducing alfalfa, etc.
4. The use of green manuring.

The scientific investigation is still going on: it has resolved itself into a study of the effects of farmyard

manure on the soil and on the plant. It is found that farmyard manure greatly increases the power of the soil to hold moisture (pl. 12; fig. 15) and also diminishes the resistance of the soil to the movements of the plow (fig. 16), and therefore, presumably, to the development of a root system. These effects are not shown, or shown only to a small extent, by artificials, and they constitute an important reason for the superior action of farmyard manure. It is further found that these effects are produced only after the manure has decomposed, a fact which may explain why the arid soils do not show the phenomena.

But there appears to be evidence, though less definite than one would like, that organic substances may have a direct effect on the nutrition of the plant, different in kind from that effected by the ordinary nutrients. The late Professor Bottomley claimed that certain organic nitrogen compounds, to which he gave the name, Auximones, greatly increased the growth of plants even when supplied only in minute quantities. His experimental technique was not satisfactory and he never quite convinced his colleagues, but one of his experiments is suggestive. A small water plant, *Lemna,* was grown in a complete nutrient solution composed of inorganic salts and free from any organic matter. It failed to multiply. A trace of nitrogenous organic matter was added and multiplication became rapid. Similar results were obtained with *Salvinia natans* (pl. 13).[7]

A curious and hitherto inexplicable stimulation of plant roots has been obtained at Rothamsted. Tomatoes grown in a steamed soil produced masses of fibrous roots (pl. 14B) which no inorganic nutrient has as yet given,

[7] Annals of Botany, vol. 34, p. 353 (1920). This result has been controverted by N. A. Clark, Jour. Ind. Eng. Chem., 1924, vol. 16, p. 249.

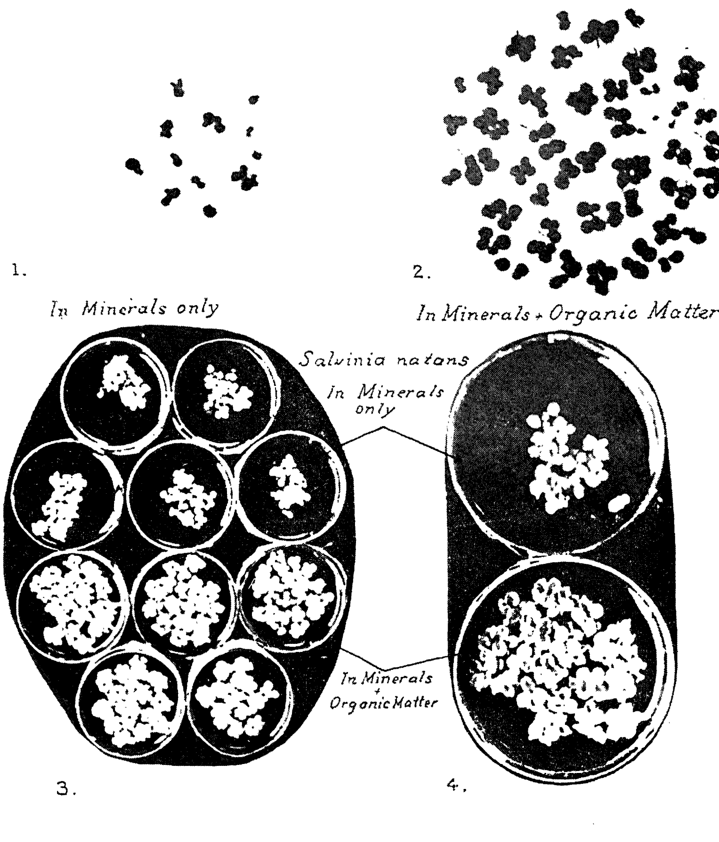


PLATE 13. Stimulating effect of organic substances on the rate of multiplication of *Lemna* and *Salvinia natans.* (From W. B. Bottomley, Annals of Botany, vol. 34, p. 353, 1920.)

though they have been produced by the use of certain organic compounds, and the effect is therefore attributed provisionally to some of the organic products of the decomposition effected by the steam.[8] On our present knowledge it is difficult to explain these results and further experiments are highly desirable. It will be remembered that Schreiner and Skinner found vanillin

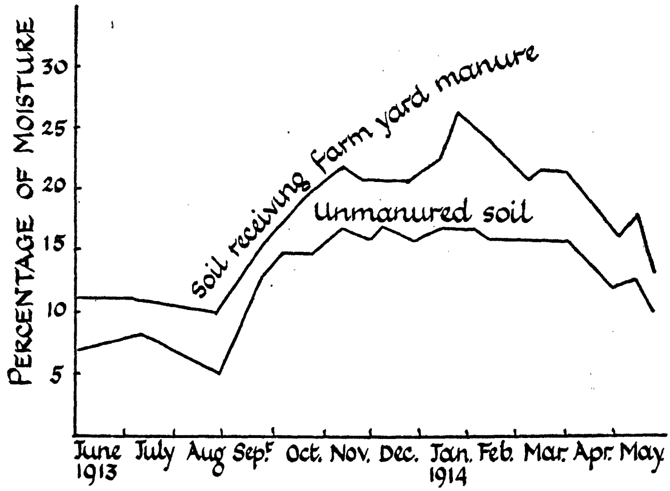


Fig. 15. Effect of farmyard manure in increasing moisture supply of soil. Rothamsted.

to have a special stimulating effect on plant growth[9] and it is possible that products of this nature are found when farmyard manure is added to soil. Picric acid and chloropicrin appear to have similar stimulating effects (pl. 14B).

Whether agricultural chemists will ever succeed in preparing substances capable of producing effects such as those on *Lemna* and tomato roots, and whether in

[8] See Schreiner, O., and Lathrop, E. C., for an account of these, U. S. Dept. of Agr., Bureau of Soils, Bull. 89 (1912).

[9] U. S. Dept. of Agr., Bureau of Soils, Bull. 87 (1912).

that event they will be able to go farther and prepare them on a large scale for sale to farmers, are matters that only the future can settle. For the present we may safely say that the long controversy between the supporters of artificial fertilizers and those of farmyard manure has ended in the way such controversies usually end—by showing that both sides had had some, but not all of the

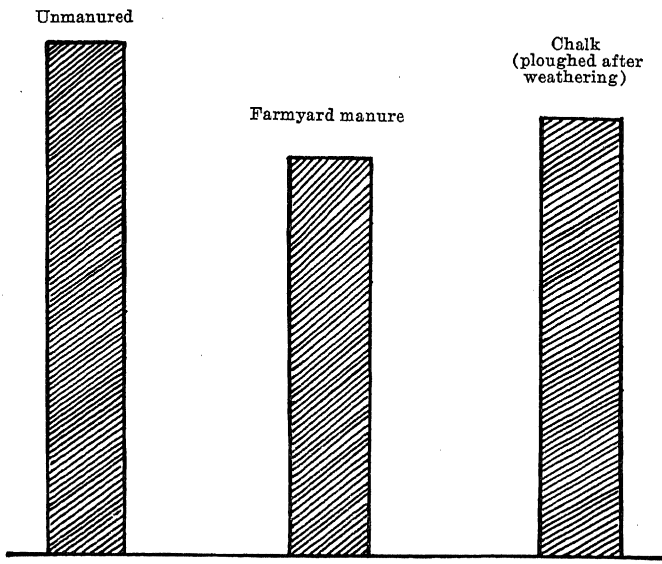


Fig. 16. Comparison of power consumption in plowing.
B. A. Keen and W. B. Haines, Rothamsted.

truth; agricultural chemists still stand by their artificial manures but they recognize the special value of farmyard manure in improving the soil moisture and tilth, and possibly in other ways benefiting the plant. The farmer is now advised to use artificial manures to ensure adequate nutrition of his plants, and to add organic matter to his soil in order to ensure such benefits as may thereby accrue.

PLATE 14A. Tomatoes supplied with increasing doses of manure. Pot 47: no manure. Pots 55–79: increasing amounts. Growth increases up to pot 72, but in pot 79, where too much has been given, growth has decreased. Pot 63 repreesnts the optimum condition for growth of fruit.

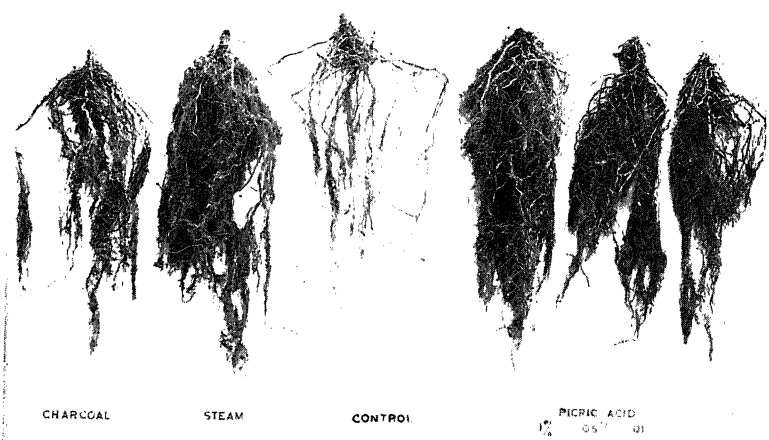


PLATE 14B. Tomato roots in untreated and in steamed soils, and in soils dosed with picric acid.

Chapter III

DECAY AND THE LIVING PLANT: *MORS JANUA VITAE*

The old agricultural investigators realized that organic matter was essential to soil fertility, at any rate under the humid conditions with which they were familiar. They also knew that organic matter must suffer decay or decomposition before it served its proper purpose in the soil: in the language of the eighteenth century, "Corruption" (using the word in its original significance) "is the mother of vegetation."

The facts are easily demonstrated in the simple pot experiment illustrated in plate 15 (opp. p. 5), in which two pots are filled with moderately good soil, and two with sterile sand or subsoil. One of each set receives fragments of grass or other vegetation which are mingled with the soil; seeds are then sown. The vegetation residues much enhance the productiveness of the good soil though they disappear in so doing; they have much less effect in the sand or subsoil from which, however, they do not disappear. It is thus shown that the residues increase soil fertility when they break down and this goes on more easily in a relatively good than in a poor soil. The experiment closely repeats the conditions in the field, for the farmer plows in stubble and clover or grass residues, while in nature dead leaves, stems, etc., are drawn into the soil by earthworms, ants, and other animals.

The necessity for decay or decomposition is well recognized by farmers. Plant residues and farmyard manure may be positively harmful if decomposition has

not taken place: straw, undecomposed farmyard manure, and vegetation residues may injure dry soils by opening them out and facilitating evaporation of moisture which can ill be spared. Farmers in the eastern counties of England (rainfall about 25 inches) use well-rotted farmyard manure on the light soils, while in arid regions farmyard manure and green manuring are not so useful as in humid regions.

Chemists have given much attention to the course of the decomposition, but the problem has proved very difficult. By the year 1843, when Rothamsted was established, three types of decomposition were known:

1. Production of nitrate.
2. Formation of the black structureless 'humus.'
3. Complete disintegration giving rise to CO_2, and simple compounds of phosphorus, calcium, magnesium, potassium, etc.

The production of nitrate during the decomposition of organic matter in the soil was well investigated by continental war departments during the eighteenth century, that being the source from which nitrates were often obtained for the making of gunpowder (pl. 16, opp. p. 60). But the connection with soil fertility was long unrecognized even after Lawes and Gilbert had shown the vital part played by nitrogen compounds in determining crop yields; it was Boussingault about 1855 who first saw the connection and thus established a relationship between munitions and fertilizers which has been vividly emphasized since 1918, when some of the high explosive factories of Europe were converted into fertilizer factories—the modern equivalent of beating swords into plowshares. The older chemists had rightly attached great importance to the formation of humus. Liebig emphasized, and as we now know, overemphasized, the

importance of the complete oxidation (he called it "eremacausis" or slow combustion) of organic matter, leaving only the mineral constituents.

Modern research has confirmed the view that these three types of decomposition represent the changes most important in soil fertility. A fourth has been added, but its significance is not yet fully worked out: the

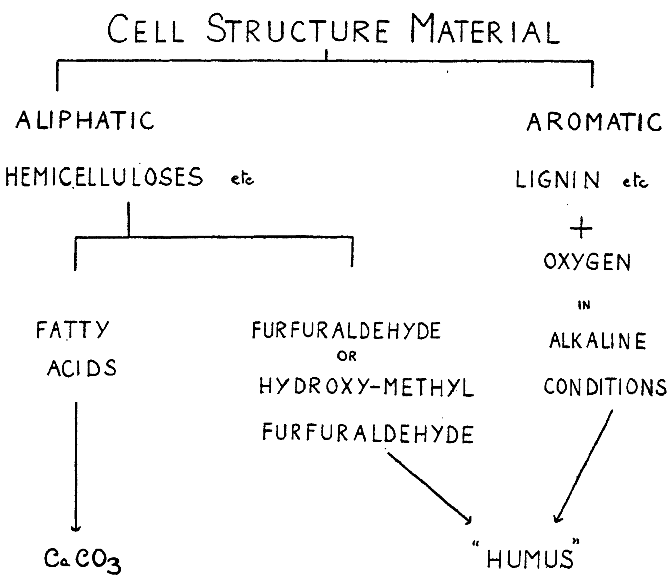


Fig. 17. Scheme showing decomposition of plant residues in soil, so far as is at present known.

decomposition of intermediate products or other substances which are toxic to plants—a process which is known to proceed actively in fertile soils. But modern work has also shown that these various changes are not different types of action, but only different phases of a complex series of changes in which all plant constituents are concerned. The details of the course of change in the

soil are not known, but so far as they have been inferred from laboratory studies up to the present they are set out in figures 17 and 9.

The proteins of the plant residues break down to amino-acids which give rise to hydroxy-acids and ammonia. The former ultimately break down to CO_2 or

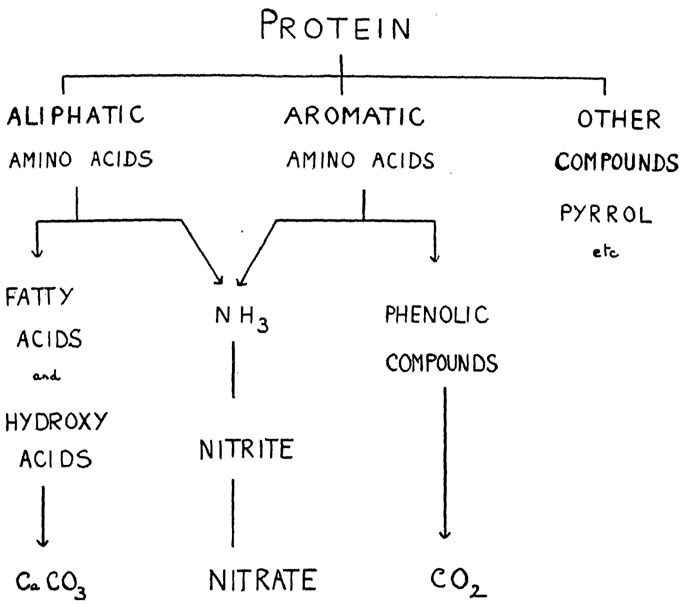


Fig. 18. Scheme showing decomposition of plant residues in soil, so far as is at present known.

calcium carbonate, though some of the more stable such as dihydroxystearic acid tend to persist, and have been isolated from soil in the elaborate studies of Schreiner at the Bureau of Soils. The ammonia is oxidized to nitrite and then to nitrate. So far as is known no humus is formed[1] but a remarkable set of products is indicated: phenolic compounds arising from the breakdown of the

[1] See Gortner, R. A., Soil Science, vol. 3, pp. 1–8 (1917).

aromatic amino-acids. Direct experiment has shown that these are poisonous to plants, but it has also failed to reveal them in the soil: if they are formed they must at once be decomposed. Sugar and starch break down so rapidly that no intermediate products are known, but the decomposition of the cell structure material is much slower; it is especially interesting as the source of humus, which apparently arises chiefly from the aromatic groupings, lignin, etc.; though the aliphatic celluloses also produce a substance of similar physical properties, though somewhat different chemically: furfuraldehyde or one of its derivatives is the probable intermediate product. Aldehydic substances were commonly found in the soil by Schreiner.

The importance of humus lies in the fact that it appears to be the chief agent concerned in the improvement of water-holding capacity and the facilitating of tilth brought about by the organic matter of the soil.

The formation of nitrate is of obvious importance in the nutrition of the plant, and it is associated with an interesting and complex group of phenomena. Nitrates are very easily lost from the soil through direct absorption by plants, by washing out, or by decomposition, so that any nitrogen transformed into nitrate may be regarded as potentially lost. No other nitrogen compounds, however, are liable to loss. A soil left exposed to weather and devoid of all plant growth loses nitrogen fairly rapidly; the lysimeters at Rothamsted lost from the top 9 inches 1124 lbs. per acre of nitrogen during the years 1870 to 1916, the initial percentage 0.146 (top 9 inches) having fallen to 0.099. Records of the prairie soils of the United States and Canada showed marked losses of nitrogen as soon as they were broken up, much in excess of the amount of nitrogen removed by the crop,

while richly manured and intensively cultivated glass-house soils show even more serious losses (fig. 19). And although the quantity of nitrogen appears to remain

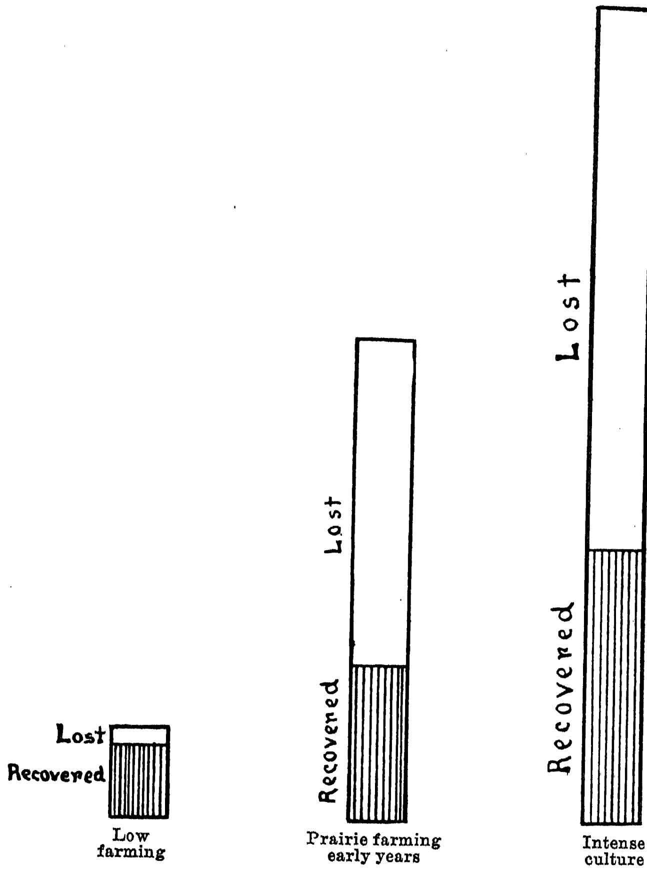


Fig. 19. Losses of nitrogen during cultivation.

unchanged when soil is left in its natural wild state or when it is covered with sod, yet closer examination shows that loss must occur, for the drainage water contains nitrates. Since then these losses of nitrogen are always

PLATE 15. Effect of plant residues on productiveness.
Pot 3: soil alone. Pot 6: soil and plant residues. Pot 4: subsoil alone. Pot 7: subsoil and plant residues.

taking place in humid regions, how is it that any nitrogen continues to survive in the soil?

This question was asked by the great French chemist, Berthelot, and was answered by him. The losses, he argued, must be compensated by fixation of gaseous nitrogen from the air, and a search was therefore begun for possible fixing agents. The farmer already knew that leguminous crops had great powers of restoring lost fertility and chemists showed that they increased the stores of nitrogen in the soil.

Chemists have therefore been led to the following conclusions:

A. Plant residues are essential to soil fertility in humid climates, but only in so far as they can decompose in the soil.

B. The most important fertility reactions are:

1. The production of nitrates.
2. The fixation of nitrogen to recoup the losses on cultivation.
3. The formation of humus.
4. The decomposition of any substance, whether intermediate product or not, which is harmful to plants.

The mechanism by which the changes are effected remained unknown for many years and became a subject of great controversy.

The solution to the problem came suddenly and from a wholly unexpected quarter. It has often happened in the history of science that the study of a purely technical problem has given the clue to some entirely distinct scientific problem; indeed this possibility has brought much consolation to men of science who perforce have had to undertake technical and empirical inquiries. Pasteur

in the course of his studies on fermentation, about 1850, had discovered that important chemical changes, and particularly oxidations, are frequently brought about in nature by microörganisms, but no one had applied this

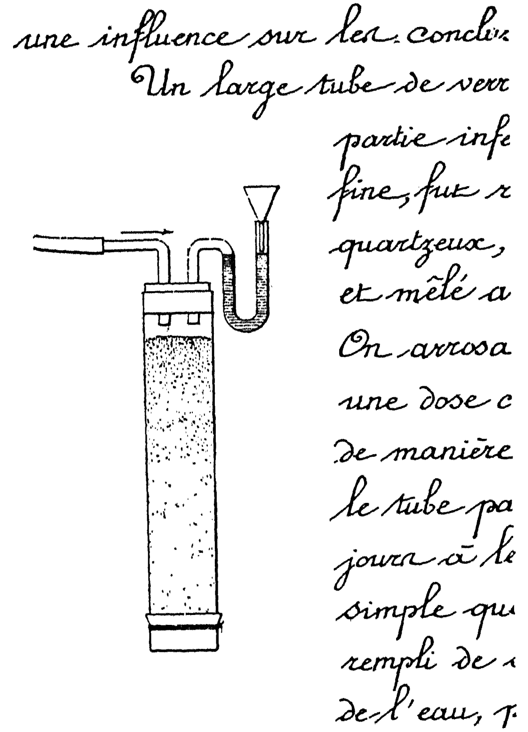


Fig. 20. Schloesing and Müntz experiment, 1877. Nitrification of sewage.

discovery to soils. Schloesing and Müntz in 1877 were asked by the municipality of Paris to study the purification of sewage, and they found that the process involved nitrification; when the sewage was allowed to trickle over chalk in the presence of air, there was at first no change, but after some days nitrification set in and

purification thereupon began. The born investigator notices trifles and profits by them: Schloesing and Müntz observed this initial delay and argued that it indicated a biological cause for nitrification; if the process were chemical or physical, it should set in at once. They accordingly blew chloroform vapor through the chalk and found that this stopped all action; they blew out the chloroform and added some soil extract and found that

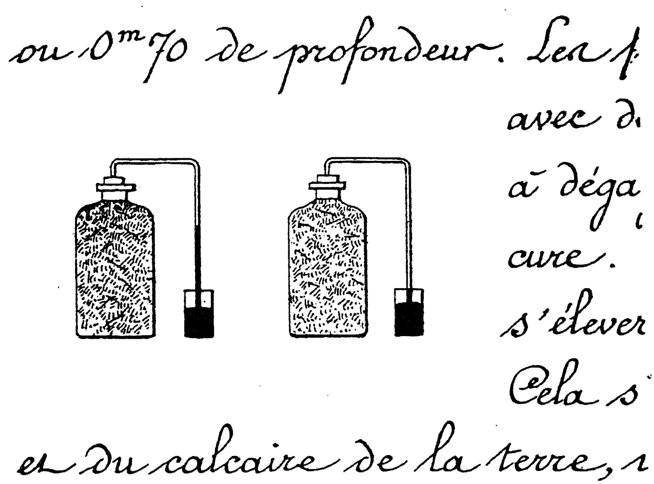


Fig. 21. Schloesing and Müntz experiment.
Respiration of soil.
(From Schloesing's lectures, reproduced by his son.)

nitrification started again; it was therefore due, they said, to a living ferment (fig. 20). Schloesing followed up this discovery by measurements of the respiration in a soil (fig. 21), and these indicated a condition of considerable vital activity. In his highly interesting and suggestive lectures at the *Ecole d'application des manufactures de l'Etat* he developed the view that the decompositions going on in the soil and upon which soil

fertility largely depends are brought about by minute living organisms. Bacteriologists became interested, and although the science was new and its technique crude, they were able to find many kinds of bacteria in the soil capable of decomposing nitrogen compounds, and even to devise methods for roughly counting them.

Naturally many attempts were made to isolate the particular organism that produced nitrates, but for years there was no success. Warington spent more than ten years at the problem,[1] using the standard methods with great care and persistence, but always without result. The crown of disappointment came when the problem was solved and the organisms isolated by a young Russian bacteriologist, Winogradsky, working in Paris, who broke away from the standard methods and recognized practice, and boldly set up new methods of his own. The result is a warning against the overorganization of research; an official group working with official methods might have labored for years without success.

The fixation of gaseous nitrogen, whereby the stock of soil nitrogen is replenished, was also traced to microorganisms. Hellriegel and Wilfarth, studying the effect of nitrate supply on plant growth in 1888, found that gramineous plants (e.g., barley) failed to grow in sand culture without a nitrogen compound, but on addition of nitrate growth took place and increased with increases in the supply of nitrate. Leguminous plants, on the other hand, behaved quite differently and most erratically; they sometimes grew, and sometimes failed to grow, without nitrogen, and on addition of nitrate they showed no regular increases in growth. It was therefore concluded that the nitrogen nutrition of the

[1] From 1878 to 1890. See E. J. Russell and others, Micro-organisms of the soil (Longmans, 1923), for further details.

leguminosae differs fundamentally from that of the gramineae, and, in the pots without nitrate, was dependent on a factor which was sometimes absent in the experiments. Bacteriological activity in soil was by this time clearly recognized, and Hellriegel and Wilfarth had no difficulty in invoking it to explain the facts. They put up a new set of pot experiments in which all the sand was sterilized; to certain pots they added a little extract of fertile soil, and then sowed leguminous crops: the results are shown in plate 17 (opp. p. 74). Search for the organism was begun in several laboratories and was ultimately crowned with success.

It is now known that a bacillus living in the soil penetrates the root hair of a leguminous plant weakened by lack of nitrogenous nutrients; it multiplies in the plant root, forming a nodule, and draws its food and energy materials from the constituents of the plant sap. It is a true parasite, but it has the remarkable power of fixing gaseous nitrogen taken from the air, and building up complex nitrogen compounds which are then passed into the plant.

It is interesting to reflect that Hellriegel and Wilfarth's experiment had been carried out by Lawes, Gilbert, and Pugh (the latter being the first American to do scientific agricultural work in England) in 1860, but the manipulation was so extraordinarily careful that everything had been sterilized although no microörganic activity was suspected, Pasteur's work being either unknown at Rothamsted or at any rate not applied. In these circumstances clover failed to grow. But a very different result might have been obtained had the Rothamsted workers been a little careless and so allowed dust carrying the organism to enter; the history of soil microbiology might have been very different.

Beside the nodule organism, two free living forms have been discovered, *Clostridium* by Winogradsky, and *Azotobacter* by Beijerinck, both of which are capable of fixing gaseous nitrogen and converting it into complex protein substances if grown without nitrogenous nutrients and amply supplied with a source of energy—

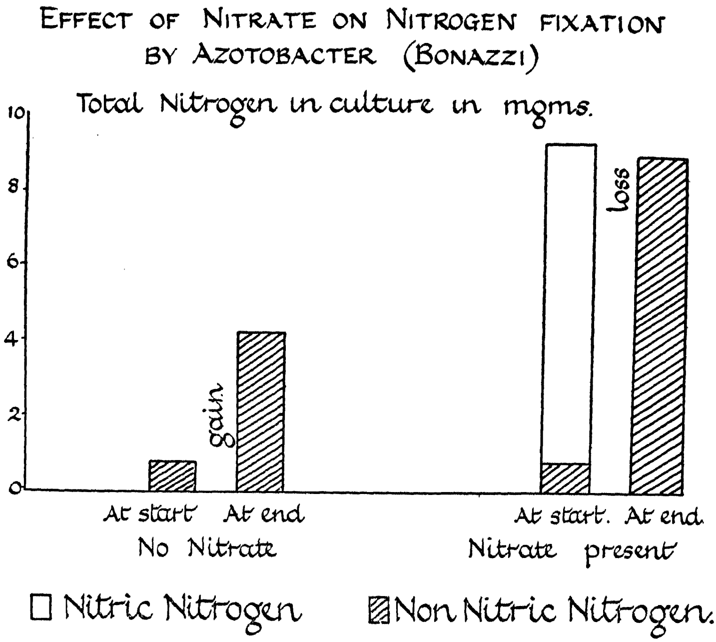


Fig. 22. Reduction of the activity of *Azotobacter* through addition of nitrate to the medium. (Bonazzi.)

preferably mannite, a sugar which occurs in Manna ash, celery, sugar cane, certain seaweeds, etc. The process is very wonderful, and no chemist can carry it out in the laboratory; but it is apparently only a response to starvation conditions, for the organisms diminish their fixation at once if a little nitrate is supplied to them and

cease it altogether, indeed bring about loss of nitrogen, if more nitrate is given (fig. 22).

Of all this ground much was broken and the general results established during the period 1880 to 1890, perhaps the most brilliant ten years in the history of soil science. Later work has shown that the soil population is far more varied, more numerous, and infinitely more wonderful than was at first suspected. Fungi and actinomyces are numerous and play a great part in the production of humus. Apparently, also, some of the soil organisms are capable of oxidizing any product of the decomposition which still contains potential energy, even though it be poisonous to most other living things. One of the most remarkable of the soil decompositions is that of the phenolic substances which, as we have seen, are formed simultaneously with the nitrates and would poison the plant if they accumulated.

Several other groups of organisms have been recognized and more or less closely studied, including the algae, protozoa, and nematodes. Of these the algae appear to assimilate nitrates, and thus to compete with plants for the available supplies; possibly also they produce some carbohydrate. Of the protozoa the ciliates occur in only small numbers; the amoebae feed upon bacteria, and tend to keep down bacterial numbers; the flagellates, one of the largest groups if measured by volume of protoplasm, are not yet investigated, and their effect in the decomposition is unknown. L. R. Cleveland has made the interesting observation[2] that termites are able to digest wood only through the coöperation of certain flagellates living in their intestines and they die of starvation if freed from these organisms and fed on sterilized wood.

[2] Biol. Bull. vol. 46, pp. 177–225 (1924).

The free living nemotodes are numerous but also of unknown function.

TABLE 7. SOIL POPULATION, ROTHAMSTED, 1922

(The figures for algae and fungi are first approximations only and have considerably less value than those for bacteria and protozoa.)

	Numbers per gram of soil		Approximate weight, lb. per acre of living organisms	
	High level	Low level	High level	Low level
Bacteria	45,000,000	22,500,000	50	25
Protozoa:				
Ciliates	1,000	100		
Amoebae	280,000	150,000	320	170
Flagellates	770,000	350,000	190	85
Algae (not blue-green)	[100,000]			
Fungi	(1,500,000)	(700,000)	1700	800

Numbers of blue green algae, actinomyces, nematodes, and other organisms are not known.

The soil population of the Rothamsted fields, so far as it is known, is given in table 7. The organisms appear to be ubiquitous; the flora and fauna being the same everywhere with two exceptions; the nodule organisms apparently occur only with the host plants, and certain phenol decomposing organisms seem to have some geographical distribution not yet understood.

The net result of all this work is to show that the great series of changes occurring during the decay of vegetation residues in the soil, and playing so great a part in soil fertility, are in the main brought about by a large population of microörganisms living in its dark recesses.

Two views have been held of the general nature of the soil population. According to the earlier idea the population is formed of specialized groups of organisms each of which is engaged in carrying out a certain part of the

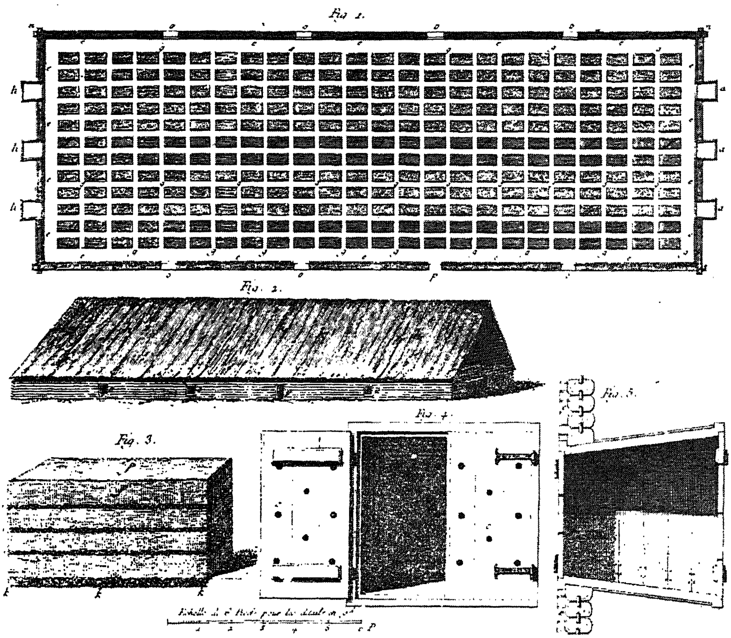


PLATE 16. Eighteenth century nitre factory. Heaps of soil and vegetable matter are made up and stored in a shed: they are kept moistened with stable drainings and like liquids. From "Description d'une nitrière artificielle, Comte de Maiby," *in* "Recueil de mémoires et d'observations sur la formation et sur la fabrication du salpêtre." Paris, 1776.

decomposition. As in a well-managed factory there was assumed to be division of labor, each organism carrying out its allotted task; and the organisms were regarded mainly as producers of plant food. By methods of pure cultures they could be picked out of the soil and studied, and so their general behavior in the soil could be ascertained. The early triumphs of the pure culture method gave a great stimulus to this view.

The second and later idea was that organisms carry out the various decompositions for the purpose of obtaining nutrients and energy; and they are not usually restricted to one reaction, but can decompose a considerable number of substances, and will sometimes effect one change and sometimes another, according as they can best obtain the energy and nutrients they need. On this view the microörganisms are no longer looked upon as solely producers of plant food; they are regarded as separate entities whose activities sometimes are and sometimes are not of advantage to the plant.

The earlier idea fitted in with the teleological conception of the universe that everything has its definite purpose in a great scheme, a conception which dominated the thought of the eighteenth and much of the nineteenth centuries.[3] Without in the least wishing to reject or even to controvert this view, it is now found better, in studying natural phenomena, to adopt an attitude of complete detachment.

[3] Teleological conceptions were very popular in the eighteenth century. Thus David Hartley (Observations on Man, etc., vol. 2, p. 245, 1749) writes: "Since this world is a system of benevolence .... let the enquirer take it for granted previously, that everything is right, and the best that can be .... let him, with a pious confidence, seek for benevolent purposes, and he will always be directed to the right road and attain to some new and valuable truth; whereas every other principle of examination, being foreign to the great plan on which the universe is constructed must lead into endless mazes, errors, and perplexities."

The idea of a predominantly specialized population has been recently revived by Winogradsky, who has devised a method for peering into the soil to see the organisms there, which is based on the fact that certain acid stains (e.g., Erythrosine) show up the living cells, but do not affect the spores or minute fragments of soil, which have hitherto rendered inspection impossible.

Applying this method to the unmanured soil of the Institut de Brie-Comte-Robert, he found only a few active organisms of a few kinds; three or four species of cocci, a few azotobacter, a little mycelium of actinomyces, and an occasional yeast; but no bacilli and no moulds. These were all the living things; he calls them the normal population. He then added various substances to the soil and incubtaed at 30° C. overnight—he attaches great importance to a short incubation only— and observed the changes in flora.

An artificial preparation of humus gave an increase in numbers, but no new forms; the flora still remained as restricted as before. Addition of any carbohydrate or protein, however, led to an instant change in the type of population; with peptone, after one night, the original population disappeared, and was replaced by two kinds of bacilli in enormous numbers. Addition of starch was followed by a great increase in numbers, but the organisms were of two kinds only, a bacillus and the mycelium of actinomyces. But the change lasts only a short time, and the population then reverts to the normal type. It is as yet too early to pass an opinion on this method, but the results agree with those obtained at Rothamsted when organic compounds are added to soil.

It seems fairly certain that some of the soil bacteria are very restricted in their activities; this is especially

true of the organisms which derive both food and energy from inorganic sources: such as those oxidizing ammonia to nitrite and nitrate; the sulphur oxidizers, etc.—organisms which seem more suited to the childhood of the world before plants had formed the organic residues in the soil, and which indeed may be the degenerate descendants of an early race of living organisms adapted to primitive inorganic conditions.

But it is quite certain that many soil organisms can effect a variety of changes in their quest for energy materials and for nutrients. This is definitely established with regard to simple products such as sugar, starch, protein, etc., which can be decomposed by a great number of organisms; it is less true, however, of more complex ones, cellulose, lignin, which are decomposed only by few organisms. Thus Doryland showed that typical ammonia producers like *B. megatherium* and *B. mycoides* leave ammonia in the culture medium only if the reaction effected for their energy supply produces more ammonia than is needed for their nitrogenous nutrition. This is the case when pure protein is decomposed, but not always when sugar is supplied; each increment of sugar furnishes more energy and therefore induces greater multiplication and more assimilation of ammonia, till finally no ammonia at all is left (fig. 23). In these circumstances the organisms become consumers and not producers of ammonia. This process goes on in the soil. Addition of protein to soil causes an increase in bacterial numbers because of the increased energy supply: it causes also an increase in nitrates since more ammonia is produced than is consumed. Addition of sugar also leads to a large increase in bacterial numbers, but the assimilation of nitrates by the organisms may be so great as completely to exhaust the stock in the soil. Substances less

rich in nitrogen than protein give intermediate effects, as shown in the experiments of Lyon, Bizzell, and Wilson,[4] in which plant roots of various nitrogen contents were added to soil and left for three months for complete decomposition. The amount of nitrate present

Quantities of Ammonia Produced from 5 grams of Casein by Pure Cultures, after Six Days' Growth, with Varying Amounts of Dextrose

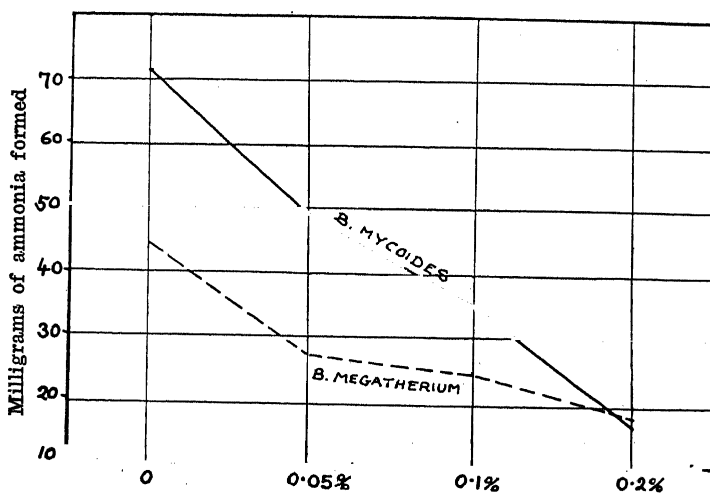


Fig. 23. Percentage of dextrose added.
C. J. T. Doryland, N. Dakota Agr. Exp. Sta. Bull. 116 (1916).

was then determined. Although the same amount of nitrogen was added in each case, the amounts of nitrate found were very different, being, as one would expect, greatest with dried blood, while there was an actual reduction in the original stock of nitrate, indicating an assimilation of nitrate from the soil, when the percentage of nitrogen in the added material fell below 1.8 per cent (table 8). These results accord with the

[4] Jour. Am. Soc. Agronomy, pp. 457–467 (1923).

well-known fact that organic substances poor in nitrogen, such as straw, are not good fertilizers, but may indeed do harm by depriving the crop of the nitrates stored in the soil.

TABLE 8. NITROGEN CONTENT OF ADDED ROOTS AND NITRATE PRODUCED IN SOIL
(Lyon, Bizzell, and Wilson)

Material	Nitrogen, per cent	Weight of roots added, in grams	Nitrogen in leachings, in milligrams
Control	....	....	946.6
Oats roots	0.45	133.3	207.3
Timothy roots	0.62	96.8	398.4
Maize roots	0.79	75.9	510.6
Clover roots	1.71	35.1	924.4
Dried blood	10.71	5.6	1751.1

(0.6 gm. nitrogen added to 28 lbs. soil: left for three months.)

TABLE 9. CARBON-NITROGEN RATIO IN SOILS

Broadbalk wheat field, Rothamsted:	
No manure since 1839	9.6
Farmyard manure every year	11.1
Woburn farm soils	10.0
Iowa (Brown and O'Neal)	12–13
Texas (Fraps)	9
Sudan	15.0

A further change sets in after the nitrate supply is exhausted. The nitrogen-fixing organisms, *Azotobacter* and *Clostridium* (which, as already pointed out fix nitrogen only when nitrates are not at hand), can now act, and may increase the store of fixed nitrogen, although in doing so they oxidize some twenty or thirty units of carbon for every unit of nitrogen fixed.

The result of these two actions is to maintain the original carbon nitrogen ratio of the soil; if this is dis-

turbed by adding more nitrogen, the excess is converted into nitrate, and so rendered liable to loss; while if it is disturbed by adding more non-nitrogenous organic matter the nitrate is assimilated and converted into protein, thus becoming protected against loss; there may also be fixation of some gaseous nitrogen at the expense of a disproportionately large amount of carbon. Thus it happens that no matter what substance is added to the soil—whether cellulose, starch, sugar, protein, farmyard manure—it rapidly undergoes decomposition in such a way that the final ratio of C/N is much the same as it was originally. In a surprisingly large number of cases in humid conditions, the ratio stands at about 10; thus it is the same on the Broadbalk plot unmanured since 1839 as on the adjoining plot receiving 12 tons of farmyard manure annually since 1843; it is approximately the same as at Woburn on a sandy soil, and as in Texas and Iowa. Only when the condition becomes fundamentally different, as in the Sudan, is there any marked change (table 9).[5]

Several interesting consequences follow. One of the most curious is that the nitrogen content of a soil cannot be increased unless at the same time the carbon content is increased ten or twelve times as much; so also it seems impossible to diminish the nitrogen content unless ten or twelve times the amount of carbon is also removed. A second interesting practical result is that the effectiveness of an organic manure is largely determined by its non-nitrogenous constituents. If it contains sufficient easily decomposable material, rich in energy, to allow the micro-organisms to multiply greatly, and insufficient nitrogen to satisfy their needs, so that they consume more

[5] For an interesting discussion of this curious phenomena, see Waksman, S. A., Jour. Agr. Science, vol. 14, p. 555 (1924).

ammonia than they produce, it will be ineffective as a fertilizer since it will diminish the amount of nitrate available to the crop. If, however, it contains insufficient non-nitrogenous energy material, the organisms will be driven to decompose the nitrogenous constituents, and may produce more ammonia than they consume; the manure is then effective. Well-rotted straw is an example of an effective, and undecomposed straw of a non-effective manure, the latter proving beneficial only when an excess of nitrogen is supplied in other fertilizers (fig. 24).

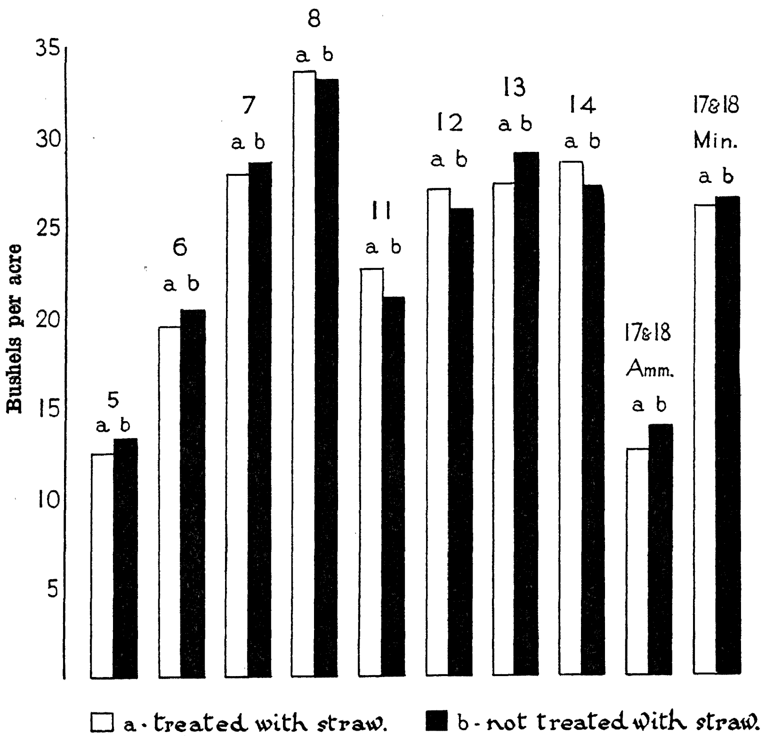


Fig. 24. Effect of straw on yield of wheat, Broadbalk field, 12 years, 1868–1879. (Plots 8, 11, 12, 14 receive more nitrogen as sulphate of ammonia than the crop needs, the other plots receive less.)

A third result is of great practical importance. Decomposition of the added substance which has disturbed the equilibrium may be so rapid that plants are unable to utilize the nitrate formed, and serious losses may ensue. Once the 'steady state' is reached, however, decomposition slows down considerably, and the rate of production of nitrate no longer exceeds the assimilating power of the plant; losses therefore become less. Thus from the Broadbalk unmanured plot there is no loss of nitrogen; from that receiving farmyard manure the loss amounts to 108 lbs. per annum over and above the amount taken up by the crop (table 10).

TABLE 10. BROADBALK WHEAT FIELD

Nitrogen balance sheet, 1865–1914: lbs. per acre, top 9 inches

	Farmyard manure annually		No manure since 1839		Complete artificials annually	
Nitrogen in soil 1914	6278		2454		3132	
1865	4260		2767		3054	
Gain or loss in soil	2018 (gain)		313 (loss)		78 (gain)	
Added in manure, seed, and rain		9800		343		4557
Taken in crops	2466		704		2154	
Left in soil	2018	4484	313	391	78	2232
Unaccounted for		5316		48		2325
Lbs. per annum		108 (loss)		1 (gain)		47.5 (loss)

The 'steady state' of slow decomposition probably represents only a mobile equilibrium between the various activities. The slow, continuous, and apparently never-ending output of nitrates from an unmanured soil is most easily explained on the supposition that part of the

nitrate formed at any time is at once assimilated by the microörganisms and is therefore saved from possible loss, though it will be reformed on their death. The process thus represents an infinite series of descending order of magnitudes. The energy material necessary for local assimilation might come from algae, of which numbers exist in the soil. Whatever the reason, the output of nitrate has never yet come to an end in any soil, however exhausting the treatment; it is still active on the Rothamsted drain gauges after fifty-four years without manure or vegetation of any sort, and it is still sufficient to produce a 10-bushel crop of wheat on land at Rothamsted which has had no manure since 1839. Soil exhaustion, in short, so far as nitrogen is concerned, is extraordinarily slow, though it may soon proceed far enough to make cropping unprofitable.

The foregoing considerations show that energy relationships play a considerable part in determining the reactions brought about by microörganisms in the soil; their importance will undoubtedly become more and more recognized by soil investigators. The source of energy for all the soil population is the organic matter built up by the plant; the nutrients also come from the same source. In return, the soil decompositions effected by the soil population furnish the nutrients essential to the plants, confer upon the soil properties of holding moisture and forming tilth, which, if not essential, are highly advantageous, and they also remove from the soil products which, if they accumulated, could not fail to be injurious to plant life. We must therefore regard the microörganisms of the soil as being in humid regions just as essential to the plant as the plant is to the mircoorganisms. The whole process is a great cycle of life. On

the one side the green plants are taking up carbon dioxide from the air and simple inorganic salts from the soil, and building them into complex organic substances rich in available energy, deriving the necessary energy for the process from the sunlight, and using their chlorophyl apparatus as the transformer—transforming very efficiently if one confines attention to the actual chloroplast

TABLE 11. ANNUAL ENERGY CHANGES IN SOIL: BROADBALK
Millions of kilo calories per acre per annum

	Farmyard manure	No manure
Added in manure	14	....
Added in stubble	2	0.3
Total added	16	0.3
Taken from soil	....	0.5–1
Stored in soil	0.5–1	....
Dissipated per annum: million kilo calories	15	1
Per day: calories	41,000	2,700
Equivalent to	12 men	¾ man
The human food grown provides for	2 men	½ man

surface. On the other side are the soil organisms decomposing the complex organic matter to obtain the energy and nutrients they need, and doing the work so thoroughly that the final residues are devoid of available energy and are the simple salts which plants can utilize. The amounts of energy transformed on two of the Rothamsted soils are shown in table 11. On a soil liberally treated with farmyard manure, energy of the order of 15 million kilo calories per acre per annum is dissipated; in a very poor unmanured soil the quantity is only about

1 million. These amounts are greater than corresponds with the human food production, and it appears that our agricultural efforts benefit the soil organism more than they do ourselves.

The distinguishing characteristic of life is change, and recent studies of the soil population have revealed a remarkable succession of changes, the cause of which, and their significance for plant growth, are quite unknown. The organisms are studied at Rothamsted in the natural field soil, the method being to take censuses of population and of nitrate production at frequent but regular intervals: the technique having been developed as a result of considerable previous investigation.[6] Owing to their long continued treatment, the Rothamsted plots show less variation than is usual with soil, and under the statistical control adopted the probable errors of the census can be estimated. The investigation is carried out, like others at Rothamsted, by a team of workers, and it has been possible to take 366 successive daily censuses of population, and, on several occasions, 30 or 40 successive two-hourly censuses of bacterial numbers and of nitrate production, the determinations being so made that their statistical value was known. The results show that the soil population is not steady in numbers, but is continuously varying.

There are seasonal changes; a rise in numbers and in activity in spring and in autumn, and a fall in summer

[6] It was an essential preliminary to develop a medium on which the colonies could grow without spreading over the whole plate or effecting liquifaction; this was successfully done by H. G. Thornton (Annals Applied Biology, 1922, vol. 9, pp. 241–274). It thus became possible to keep the plates in the incubator sufficiently long to allow multiplication of the slow-growing organisms, which, as Conn had already indicated, appear to be the most important forms in the soil. With the older media, only a few days' incubation was possible, so that these forms were missed. For a discussion see N. R. Smith and S. Worden, Jour. Agr. Res., vol. 31, p. 501 (1925).

and in winter—a type of fluctuation which is apparently shown by plankton both in the sea and in lakes (fig. 25, 26). It is not known whether the rise in bacterial numbers represents a general uplift of all forms, or the temporary emergence into prominence of a few special ones.

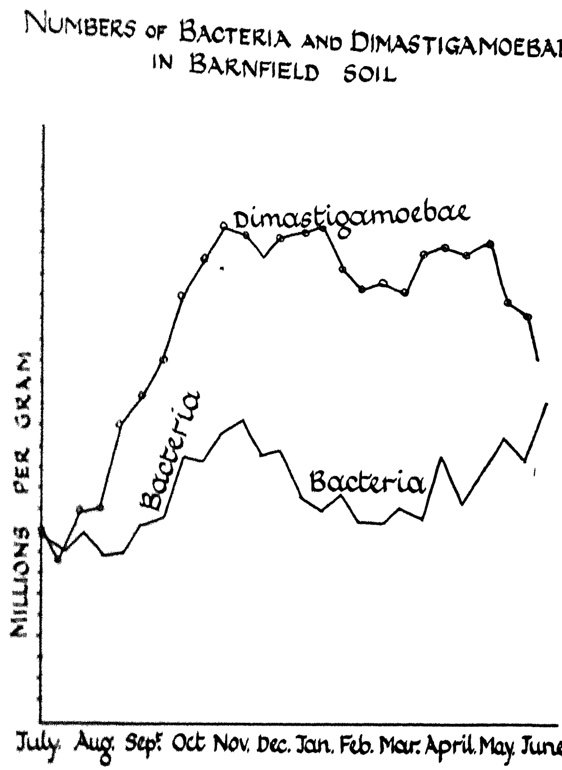


Fig. 25. Seasonal changes in numbers of soil organisms (Cutler, Crump and Sandon).

In addition there is remarkable daily fluctuation. The bacteria fluctuate inversely as the active amoebae, rising in numbers as the amoebae fall, and diminishing in numbers as the amoebae rise (fig. 27); this is traced to

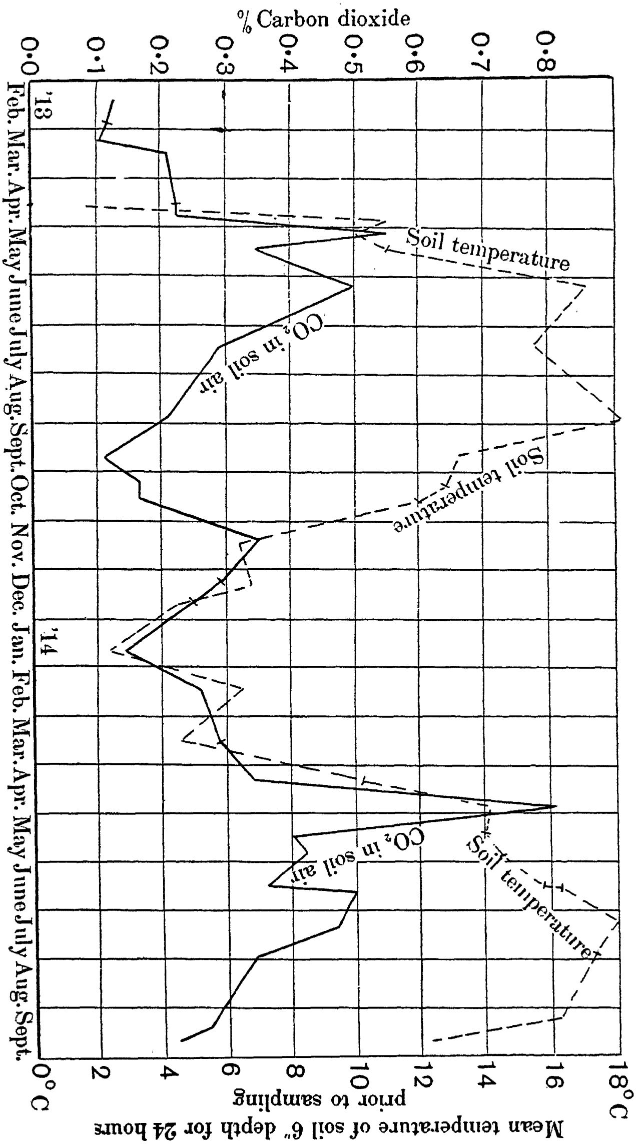


Fig. 26. Curves showing percentages of CO_2 in air of Broadbalk unmanured plot of mean soil temperature.

the fact that amoebae feed on bacteria.[7] But the fluctuations of the amoebae cannot be explained; they are not obviously related to temperature moisture or rainfall. One of the protozoa, *Oicomonas,* shows a definite periodicity which, however, is equally inexplicable.

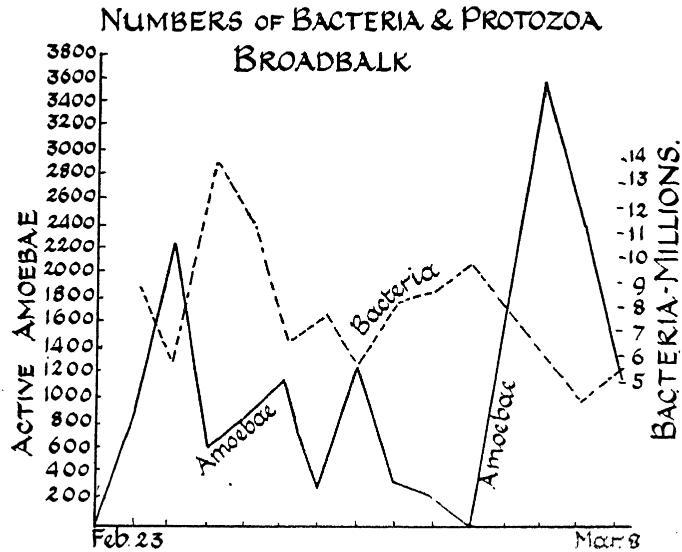


Fig. 27. Daily fluctuations (D. W. Cutler, L. M. Crump, and H. Sandon).

The two-hourly censuses also showed marked fluctuations, but, owing to the labor involved, the determinations are confined to bacteria and nitrates (figs. 28, 29). The nitrates vary from day to day and apparently (though this is not fully established) from hour to hour

[7] This was established by inoculating cultures of amoebae into a sterilized soil to which bacteria had been added; the numbers of bacteria fell and, at their lower level, showed fluctuations characteristic of normal soil. Without the amoebae the numbers remained high and steady (Cutler, D. W., Ann. Applied Biology, vol. 10, pp. 137–141, 1923). The daily fluctuations were established by D. W. Cutler, L. M. Crump, and H. Sandon (Phil. Trans., vol. 211, pp. 317–350, 1922).

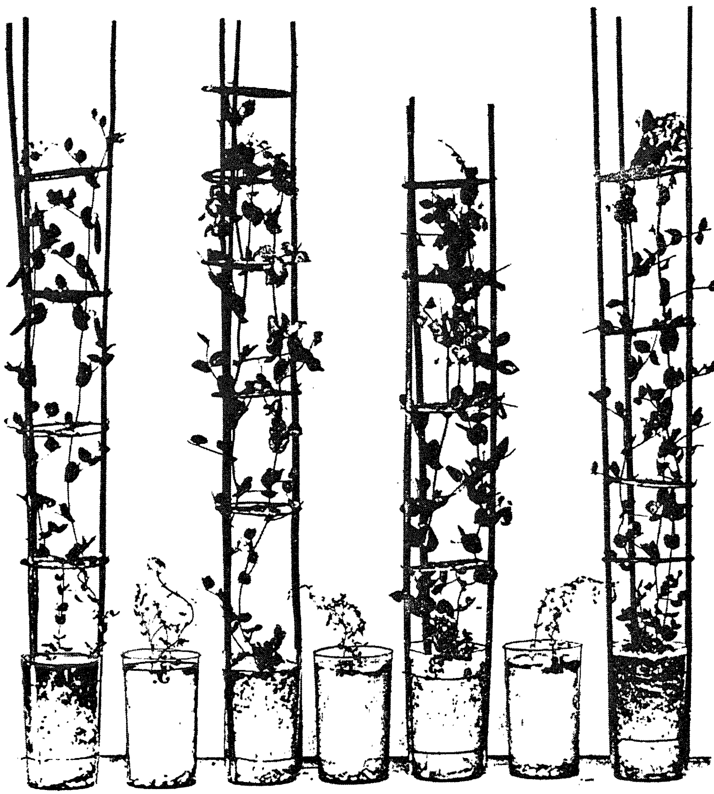


PLATE 17. Hellriegel's and Wilfarth's experiment with peas. All are growing in sterilized sand but in the four pots placed alternately, which show good growth, extract of garden soil has been added. (Zitschr. des Vereins f. d. Rübenzucker-Industrie, 1888.)

even in absence of rain and of vegetation; it appears that production and assimilation proceed simultaneously, sometimes one, sometimes the other, predominating.

It seems probable that the plant has become adapted to this perpetually variable activity in the soil, and that plant nutrition in nature is also a fluctuating phenom-

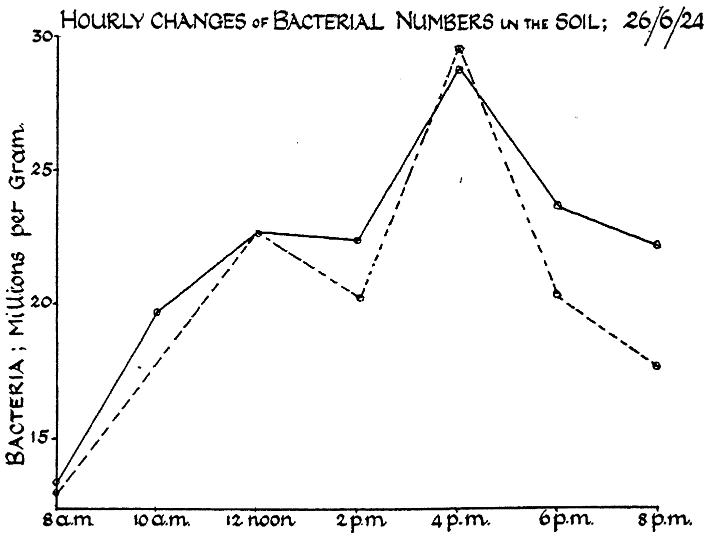


Fig. 28.

enon. The variations in nitrate imply variations in the bases—calcium and possibly others—and suggest a soil solution of ever varying composition. Clearly the uniform speed of output and the straight-line conditions dear to mankind are not nature's way. What these fluctuations and variations may mean, there seems no way of knowing. A deaf, blind man in a cathedral where the organ was being played by a master might trace out rhythms, sequences, and periodicities in the vibrations of the woodwork and the air; he might plot endless

curves to express his observations; but he would never hear the music. And it may well be that these strange pulsations shown in the life of the soil microörganisms—life so inextricably linked up with our own—will be forever beyond our understanding.

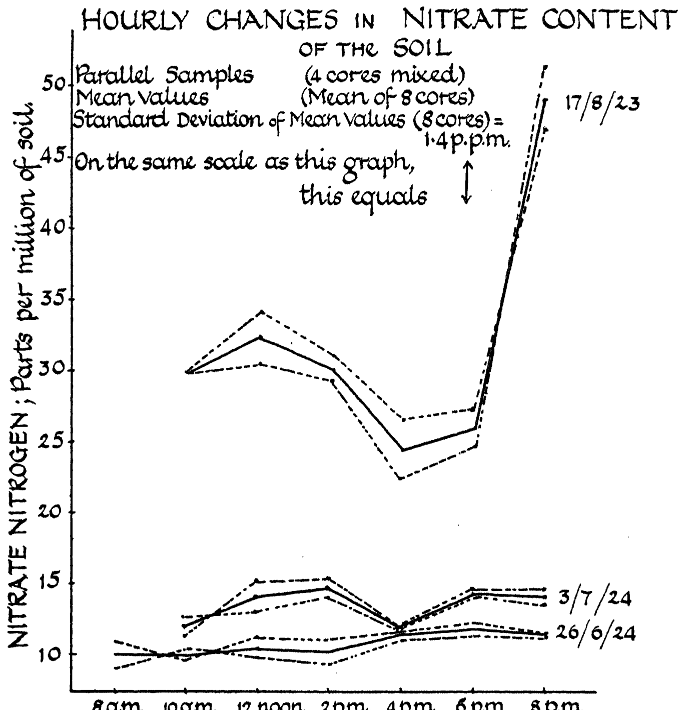


Fig. 29. Replicated samplings showing variations in nitrate on a uniform plot of ground on days free from rain (H. T. Page and H. G. Thornton).

Chapter IV

THE SOIL MICROORGANISMS: CAN THEY BE CONTROLLED AND UTILIZED?

As soon as the importance of the soil microörganisms in fertility was recognized, attempts were made to effect some degree of control. None of them has as yet become important in practice, but good progress has already been made and the work is still in its infancy.

Three general methods have been tried:

1. The introduction of special microörganisms desired for some particular purpose.

2. The modification of the soil conditions so as to favor or discourage the development of particular organisms or groups.

3. Attempts to kill organisms which are not wanted.

The earliest attempts at control were all by the first method, chiefly in connection with leguminous crops. Hellriegel and Wilfarth's striking experiment in 1888 (pl. 17) suggested at once the advisability of adding cultures of the nodule organisms to soils on which leguminous crops failed to grow well, and many attempts were made by Nobbe and Hiltner about 1896 on the poor sandy soils around Münich. Some striking successes were obtained, and barren sandy heaths after inoculation carried good crops of clover, vetches, and other leguminous plants. The method was introduced elsewhere, but its success was very limited; it proved of so little help in England that it never became a farm practice. But the soundness of the principle was recognized, and it was

felt that failure was due to ignorance of the proper conditions; the laboratory investigations were therefore continued.

One reason for failure, especially with the clover and pea crops tested in England, was that the organisms were already present in the soil, but some adverse soil condition prevented the development of the plants: to increase their numbers further by inoculation was therefore useless. Attempts were made to isolate and use more virulent strains than those normally occurring in soils, the principle of varying virulency having been established in Pasteur's classical experiments on animal diseases. Hitherto the efforts have failed; there is, however, a recent indication that the growth of one leguminous crop may intensify the infection of a subsequent crop: the inoculation of lucerne is said to be rendered more secure by first growing *Mellilotus Alba* and then plowing it under before the lucerne is sown.

More frequent successes were obtained with leguminous crops grown for the first time in a district. The organisms are specific to certain crops or groups of crops. Most soil organisms are universally distributed p. 60), but the nodule organism is an exception; it occurs only along with the host plant. Investigators have therefore left alone for the time the problem of inoculating crops already established in a district, and they have confined their attention to the more promising case of leguminous crops not previously grown. Agricultural conditions have of recent years brought into prominence lucerne or alfalfa, a crop which, though well known to experts[1]—having been cultivated in Asia

[1] It is mentioned in Theophrastus, "Enquiry into Plants." Sir Arthur Hort has published an excellent translation of this extraordinarily interesting work in Loeb's Classical Library.

Minor by the ancient Greeks, in Spain by the Moors, and in Flanders and England for several centuries—was not commonly grown on farms. This crop has therefore received much attention from bacteriologists, and already good results have been obtained from inoculation: constant improvements are being made. The story of the process is a succession of efforts to overcome difficulties, efforts which after many failures were crowned with success. One of the first was the difficulty of keeping the organisms in an active condition; many of the cultures sent to the farms were either dead or moribund before they were used. This problem was studied in Scandinavia, and a good working solution found. C. Bartel, the Swedish bacteriologist, discovered that soil bacteria survived much better in a sterilized soil than on the agar media then commonly used: he therefore kept his organisms in sterilized soil, and transferred to agar only when sending them out for use; upon reaching the farm they proved far more effective than the older cultures. They were mixed with water and sprinkled onto the seed. Many successes were obtained, but there were numerous failures, due, apparently, to the death of the organism before the seed had germinated. This difficulty was overcome by Harald R. Christensen, of Copenhagen, who used milk instead of water as the propagating fluid; i.e., the culture as received on the farm was mixed with milk and then put onto the seed. This had been done before by Hiltner and Störmer in 1904, but it was not usual in practice.

Meanwhile the life-cycle of the organism was studied by Hutchinson and Bewley at Rothamsted, and was found to be complex, including both motile and non-motile forms; only in the motile condition could it invade the plant roots. Phosphates caused the organism to

pass from the inert to the motile stage. H. G. Thornton at Rothamsted therefore further modified the process by adding phosphates to the milk, thus ensuring a speedy commencement of motility after the culture is added to the soil. The details of the method as now used are set out on page 93. They involve:

1. Keeping the culture in sterilized soil so as to ensure viability; transferring to agar only for the minimum time necessary for transit to the farm.

2. Using milk as the inoculating fluid.

3. Adding phosphates to the milk to ensure rapid passage from the non-motile to the motile stages.

Inoculation has become very popular in Denmark because it has enabled farmers successfully to grow lucerne, which is of great value to them. Denmark, being an important producer of pig meat and dairy produce, stands in need of heavy-yielding fodder crops having high nutritive value. Lucerne was obviously indicated as highly suitable. It was not altogether a new crop to Denmark; it had indeed been tried there in the eighteenth century,[2] but without success, and throughout the nineteenth century it never became common. Later experiments showed, however, that it would succeed if the necessary organisms were added to the soil. Practical problems are rarely simple, and it was found that inoculation by itself was not sufficient to ensure good crops. Many of the soils were acid, and successful growth of lucerne was not possible till the acidity had been neutralized.

As no farmer would wish to use more lime than is necessary, it was desirable to find some method by which

[2] It is described in the interesting agricultural survey of Denmark published in Copenhagen in 1803 under the title Agerdyrkningens Tilstand Sjelland og Moen: Danmark.

an analyst could tell exactly how much was required. Christensen therefore developed a biological test for acidity so that he could advise farmers how much lime to use. Successful results followed adequate liming. The experimental work at the agricultural stations had been carried out between 1905 and 1910; by 1923 no fewer than 25,000 farmers in Denmark were using the method and obtaining increases which varied from 20 to 500 per cent over the yields of the uninoculated crops.

Another example of inoculation is furnished in the cultivation of orchids. These plants grow successfully when in association with their specific Mycorrhiza, and one method in the art of orchid-growing is the introduction and development of the proper organism in the soil.

In both leguminous and orchid cultivation definite organisms are introduced into pure cultures. Inoculation of masses of mixed organisms is practiced in certain reclamation schemes. Both in Holland and Belgium it is usual to give newly reclaimed land a small dressing of a compost made up of farmyard manure and soil. Rigid proof is lacking, but the simplest explanation of the beneficial results is that the normal soil population is more speedily set up.

The second method of controlling the soil population is to alter the conditions so as to make them more favorable or more unfavorable to a particular organism or group of organisms, and thus to encourage or repress it either directly or by a change in the equilibrium. An illustration is afforded by the soil reaction; this can be shifted toward alkalinity by addition of lime, or toward acidity by addition of sulphur, alum, sulphate of iron, or numerous other salts; the varying degrees of reaction are measured as a hydrogen ion concentration—

the pH value of Sörensen. Certain ranges of reaction are favorable to some organisms and unfavorable to others. Thus the nodule organisms of most of the common leguminous crops do not usually thrive in conditions more acid than is indicated by $pH = 6$; they could therefore be removed from a soil by acidifying to this degree, or alternatively they can be encouraged by shifting the reaction further toward neutrality.

Another illustration is furnished by the potato scab (*Spongospora subterranea*); this does not usually grow successfully in the soil at an acidity greater than 5.2, and it has accordingly been kept in check by J. G. Lipman and his colleagues by ensuring this degree of acidity. The potato itself is more tolerant, and there is a certain range of acidity over which it grows but the disease organisms may not.

Variations in temperature conditions also affect the activities of organisms and are used under glass for the control of soil pests. Tomatoes grown under glass in England suffered from *Verticillium* wilt, but it is now found that a small temperature change reduces the activity of the organism. L. R. Jones at Madison has studied other cases.[3] These methods of control are only partial, as the persistence of an organism in the soil is usually affected by a number of factors and is rarely determined by one alone.

Several attempts have been made, and with some degree of success, to control the free-living nitrogen-fixing organisms in the soil (*Azotobacter* and *Clostridium*) and thus increase the stock of soil nitrogen without the necessity of adding farmyard manure or of growing a leguminous crop. This would be useful in cases where for any reason it is undesirable to disturb the cropping

[3] Trans. Wis. Acad. Sci., 1922, p. 20.

No sugar. Sugar.

PLATE 18. A Koch's experiment. Increasing nitrogen fixation in soil through the addition of sugar. (From Jour. f. Landw., vol. 55, pp. 355–416, 1907.)

of the land. The principle that has been adopted is to increase the amount of non-nitrogen energy material in the soil, and so facilitate the development of organisms which are independent of nitrogen compounds and can obtain their necessary nitrogen from the air. The experimental work was carried out by Alfred Koch in Göttingen in 1907;[4] he added successive small doses of dextrose to moist, well-aerated soil kept at a temperature of about 20° C. and found that there was an increase in the percentage of nitrogen in the soil. Pot experiments showed that the fixed nitrogen speedily became available for plants, and thus much enhanced the soil fertility (pl. 18). Although the method appears hopelessly unpractical, it is as a matter of fact not only possible, but relatively easy, to carry out on sugar cane plantations so placed that molasses cannot profitably be sold; this waste sugar can be added to the soil when the temperature is sufficiently high. This was actually done, with good results, in Mauritius on Mr. Ebbel's estate.

Later experimenters encountered the difficulty which both Koch and Ebbel somehow missed, and to which reference was made in the preceding chapter: that the addition of energy material encouraged not only the nitrogen-fixing organisms but others as well; bacterial multiplication went on so rapidly that the soil nitrates were drawn upon to provide nitrogenous nutrients; crop production therefore fell off. Peck tried the method in Hawaii, as did also Harrison in British Guiana, but neither succeeded.

The difficulty can apparently be overcome by careful selection of the time for adding the energy material. The first effect is to cause a multiplication of many kinds of organisms, and a consequent absorption of soil nitrates.

[4] Jour. f. Landw., vol. 55, p. 355 (1907).

This is immediately harmful to the fertility of the soil, but it soon proves beneficial; for the *Azotobacter,* which is unable to fix nitrogen in the presence of much nitrate, now has no such hindrance and is able to fix nitrogen if the temperature is suitable. The energy material must therefore be added sufficiently long before the crop is sown to allow these actions to complete themselves.

The necessity for this is well shown in the following results obtained on Hoos field, Rothamsted, where the spring applications of sugar or starch, made just before sowing, were harmful, while the autumn applications made some months beforehand were beneficial (table 12).

TABLE 12. HOOS FIELD BARLEY

Effects of sugar (or starch) on the amount of produce. Plot 4.0. Complete minerals

	Time of adding sugar	Total produce, lbs. per acre	
		Without sugar	With sugar
1906	Spring	2485	Failed
1907*	Spring	3578	3249
1908	Spring	1820	1404
1909	Spring	3148	2261
1910	Autumn	2082	2502
1911	Autumn	1244	1915

* Starch applied instead of sugar in 1907.

These facts have still to find application in agricultural practice. At present nitrogenous organic matter is obtainable more cheaply than nitrogen fixed by the free-living bacteria, but it may not always be.

No direct attempt is made to control the soil organisms effecting decomposition, although presumably cultivation operations, green manuring, and farmyard manure are all advantageous.

A successful attempt has been made, however, to bring about the decomposition of straw which, as farmer's experience and direct experiment alike prove, is useless as a fertilizer for non-leguminous crops[5] or even positively harmful in its undecomposed state, though it

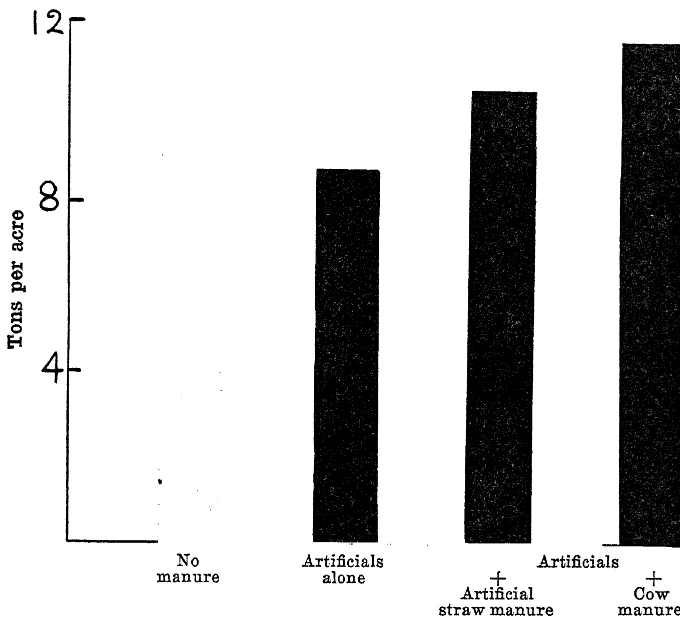


Fig. 30. Fertilizing value of artificial straw manure.
E. H. Richards. Potatoes, 1922.

becomes a valuable fertilizer after decomposition; the reason has been discussed on page 67 (see also fig. 30). The decomposition is effected in farm practice by throwing the straw into yards or buildings in which are animals —usually bullocks or pigs—and allowing it to become well mixed with the animal excretions. Studies of farm-

[5] It is shown at Rothamsted by H. G. Thornton that this is not true of leguminous crops since straw affects the numbers of nodules on the roots.

yard manure and of the changes it undergoes in making and on storage suggested a means of effecting the same end without the use of animals. It was known to farmers that the decomposition of the straw, technically called the 'making' of the manure, went on more easily in a 'rich' manure from animals fed on cake or other concentrated feeding stuffs than in a poor manure made without them. Chemists showed that the 'rich' manure contained more ammoniacal nitrogen than the 'poor' manure, and also that a considerable part of this nitrogen was transformed into more complex forms during the 'making' process. The conclusion was drawn that the microörganisms concerned have ample energy supply in the easily oxidizable non-nitrogenous constituents of the straw to allow of free multiplication, but they have insufficient nitrogen for purposes of nutrition, and therefore they assimilate the ammoniacal nitrogen from the animals' liquid excretions. This view satisfactorily accounts for the observed facts.

The Rothamsted workers investigated the possibility of decomposing straw without using animal excretions as the nutrients for the microörganisms. Straw was moistened and treated with ammonium carbonate; decomposition proceeded and a black amorphous product was obtained exactly resembling in appearance farmyard manure (pl. 19). The process is indeed identical in every detail with manure-making except that the organisms derive their nitrogen from ammonium salts instead of animal excretions.

The method has proved of much interest to farmers who have straw but insufficient animals to convert it into manure. Decomposition proceeds most economically when 0.7 parts of nitrogen (i.e., 3.5 parts of ammonium sulphate) are added for each 100 parts of straw. The

PLATE 19. Straw being converted into manure by microörganisms, without the use of animals.

nitrogen is rapidly assimilated, and dry matter is lost up to 20 per cent of the weight of the straw. The decomposition then slows down considerably,[6] until about 50 per cent of the dry matter has been lost; beyond this there is little further change, and the final product appears to represent some chemical stage since materials of different origin give a similar residue containing about 2–2.5 per cent of nitrogen. Practically no nitrogen is lost in the process, though all the ammonia is converted into complex compounds.

Farmyard manure undergoes the same kind of changes, and rots down to a similar degree. One ton of straw can be utilized for every 100 lbs. of digestible protein in the food;[7] the 'making' goes on rapidly at first, more slowly afterwards; up to 50 per cent of the dry matter may be lost, but if the manure is sheltered from rain and wind there need be little loss of nitrogen though much of the ammoniacal nitrogen becomes converted into complex proteins. The parallelism between the 'natural' and the 'artificial' manure is complete.

The transition from the laboratory to the field is always difficult. In the first great application of science to agriculture the exploitation had been kept quite distinct from the scientific work (p. 11). A similar method was adopted in the present case; the process was handed over to a syndicate, "Adco," which undertook to retain no profit beyond 5½ per cent on capital outlay, any excess to be given to agricultural research institutions;

6 The slowing down is in part the result of the exhaustion of lignin, and of the soluble carbohydrates, xylose, etc., which facilitate the decomposition.

7 With this quantity of straw it is necessary to add water, as the volume of animal excretions is insufficient to moisten the whole mass, and, moreover, the undiluted urine may be too concentrated to allow full activity of the microörganisms, at any rate until some of the ammonia has volatilized.

this arrangement was made possible through the generosity of Lord Elveden, and it has relieved the research institution of development work for which it was wholly unsuited. Thousands of tons of straw and other waste vegetable matter are now being treated annually by this process in different parts of the world, and converted into valuable manure (pl. 20). Steady improvements are being made, one of the latest being the addition of phosphates in order to hasten still further the bacterial activities. Moreover, the supplies of added nitrogen and phosphates can be adjusted to a nicety so as to reduce waste. As has happened before, the introduction of the new process into practice opened up a number of important scientific problems, some of which, concerning the decomposition of straw, are now being attacked in the laboratory.

The method of controlling the soil population by killing undesirable members has been developed at Rothamsted and elsewhere in connection with studies on partial sterilization of soils. As has often happened, the first observation was made by a practical man, Oberlin, a vinegrower of Alsace, who noticed that the treatment of vineyards with carbon disulphide in order to kill phylloxera caused an increase in growth having all the appearance of that brought about by a nitrogenous fertilizer. Scientific investigations showed that any volatile poison, or heat, had the effect of increasing bacterial numbers and ammonia production, which in turn caused increases in plant growth. The action is complex, several factors being involved, but it has been shown at Rothamsted that one factor is the suppression of amoebae which destroy bacteria. The adoption of killing methods simply to increase bacterial activity would not be economical in farm practice under present conditions, but it becomes

of great value in glasshouse practice where it is necessary to remove disease organisms from the soil. Practical growers have for some years used heat for this purpose, and they have developed methods, such as the 'pan' or 'tray' method, for doing it economically (pl. 20A; fig.

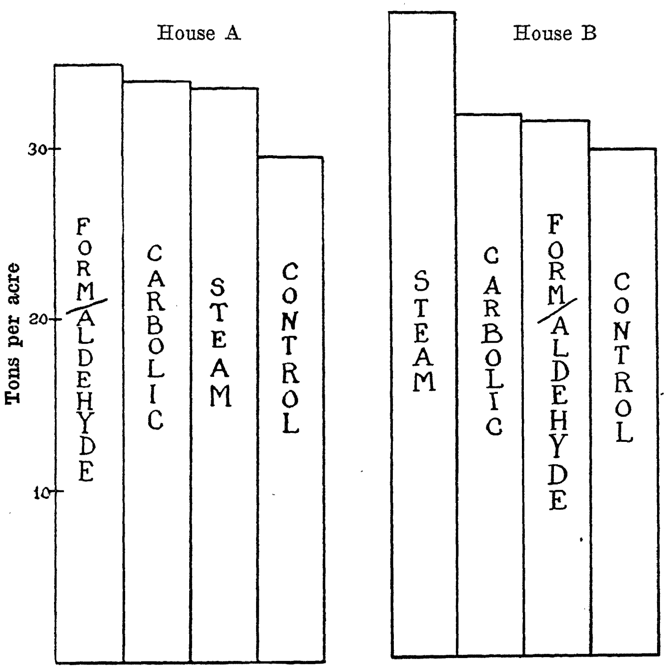


Fig. 31. Nursery No. 1. Tomato experiments, 1919–1922. Partially sterilized soils. Average for four years.

31): this method has been studied by Stone, of Massachusetts. But however steaming is done it is costly, varying in England from £80 to £300 per acre with labor at its present price (June, 1924) of 1/- per hour, and coal at £2 per ton; the minimum amount of coal necessary is about 16 tons per acre, while labor is not less than 600 hours and may be much more. Fortunately the

returns are even greater and may amount to anything from 5 to 20 tons per acre of tomatoes, worth in the wholesale market some £50 per ton. The value of steam treatment for removing eel worm from the soil is shown in plate 20B.

The scientific workers have gained a more definite conception of the objects to be achieved, and search is being made at Rothamsted for chemical agents which will effect the same purpose at less cost. The obvious method of utilizing industrial waste products is less useful than might be expected owing to their liability to change; the first investigation is directed to the discovery of the organisms to be put out of action and the testing of chemical compounds in a definite systematic manner, so as to obtain information as to the relationships between chemical constitution and effectiveness. The proper quantity and the suitable time and method of application have all to be determined by direct trial, while laboratory experiments are made to discover more particularly the precise actions going on. The interesting result is that small quantities of organic substances, such as the cresols, still more the dichlorcresols, and best of all the chlornitro derivatives, such as chlorpicrin and chlordinitrobenzene, are able to produce substantial crop increases when applied to soil in proper quantity, though it is not yet known how far the effect is due to removal of disease organisms, and how far to improvement in nitrate production or to direct stimulation of the plant (fig. 32).

The addition of small quantities, such as 2 cwt. per acre of some of these substances, has given no less than 5 tons per acre additional yield of tomatoes grown under glass, which the owner sold for a sum between

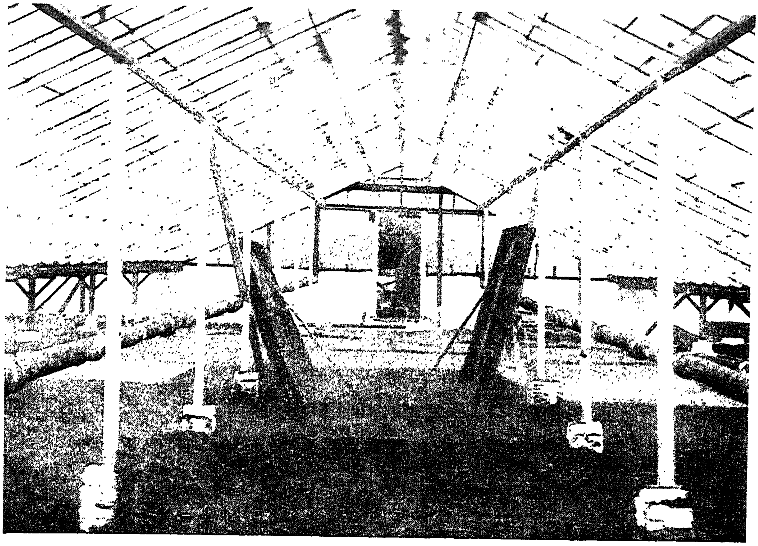


PLATE 20A. Steaming soils in glass houses: the tray method. Adopted in the Lea Valley.

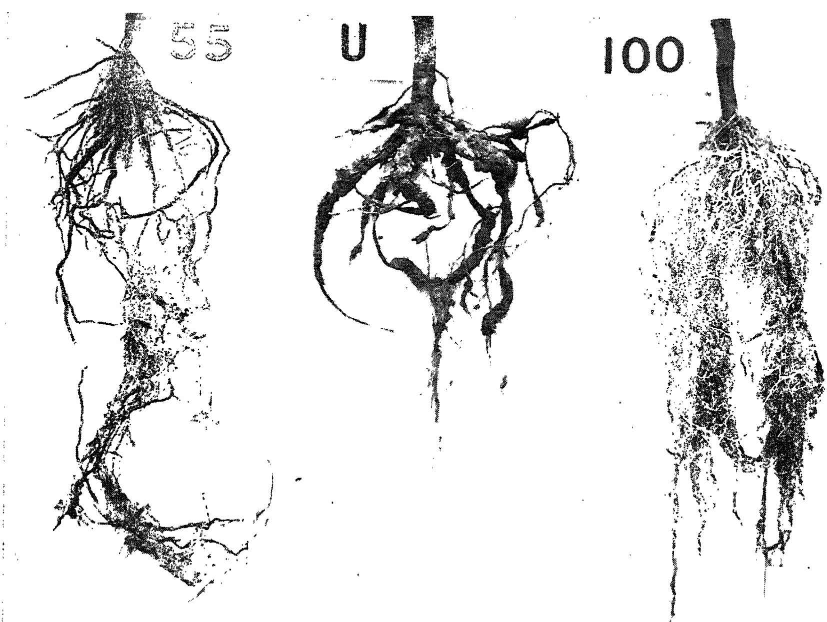


PLATE 20B. Root knot (*Heterodera*) successfully controlled by steam. U, untreated soil, badly infested; 100, *Heterodera* killed and action stimulated; 55, *Heterodera* killed but no stimulating action shown.

£250 and £300 (fig. 31). It is true that these substances are not now on the agricultural or horticultural markets, but there is no limit to the possibilities of

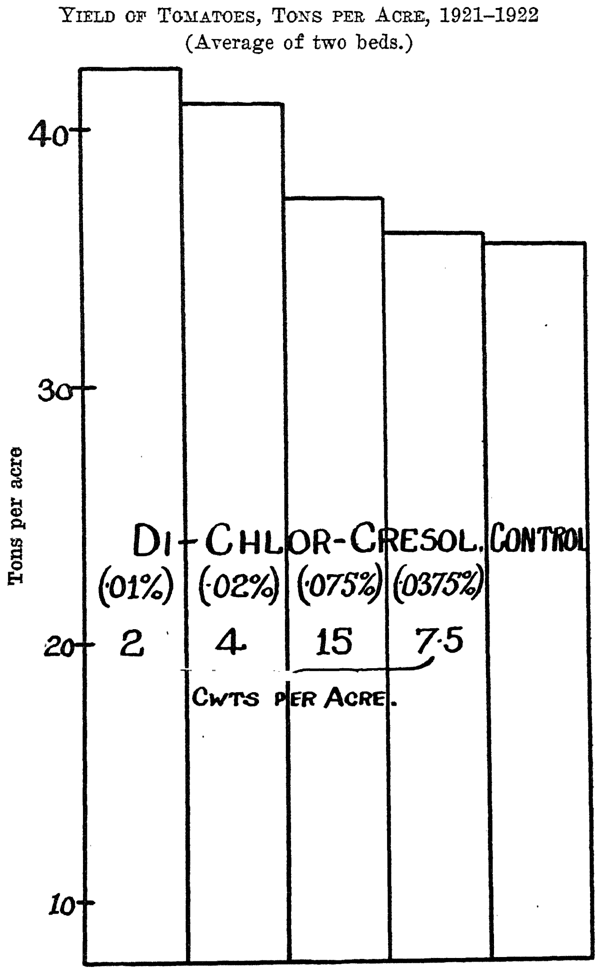


Fig. 32. Experiments to find suitable dressings of partial sterilizing agents.

organic chemistry. An industry like that of making dyes may produce as intermediates substances of the very type needed for soil sterilization, for insecticides, and fungicides. There seems a great field open for technical chemists here. Although the practical application is not yet achieved, we can safely say that a beginning has been made with the important problem of controlling the microörganisms of the soil, and altering the population so as to make it more suitable for the production of crops. The natural vegetation on the surface of the earth has long since been brought under control, and generations of growers and experimenters have gradually produced from the wild forms the immense variety of cultivated forms we now possess; the change has been very slow but it has been so great that the final forms familiar to us can hardly be recognized as even remote connections of the original wild ancestors. So, also, the present domesticated animals have been derived from wild ones; they have been selected, improved, and altered so completely that even their origin is now difficult to trace.

Will it ever be possible to alter the soil population so as to make it as superior to the present wild forms for the promotion of soil fertility as the cultivated plants and animals are superior to their wild ancestors from the food production point of view? We cannot say; but only a very rash man would venture to set limits to the possibilities of science; for the last two generations the fantastic dream of one day has been the achievement of the next, and it may well happen that this new world of soil microörganisms now opened for men of science to conquer will yield as rich a harvest as that given by the world of plants or of animals.

Appendix to Chapter IV

Directions Issued to Farmers in Great Britain for Inoculating Lucerne Seed with the Cultures of Nodule Bacteria, the Cultures Being Sent Out from Rothamsted on Agar in Test Tubes.

1. Keep the cultures in the dark until used.

2. In the cultures, the bacteria appear as a whitish slime on the inclined surface of the jelly medium.

3. Transfer the contents of the tube into fresh skim milk, using about ¼ pint of milk, and 1 gram per quart of calcium phosphate per tube of culture. Turn out the contents of the tubes using a clean stick, and *thoroughly mix the bacterial slime* with the milk, picking out the lumps of jelly medium. Rinse the tubes out into the milk.

4. The seed should be piled on a clean surface and the milk poured onto it and well-mixed with the seed, so that *every seed* is moistened with milk. It usually takes about a quart of milk to every 24 pounds of seed. If there is not enough milk add a little clean water till all the seed is moistened.

5. The seed should be sown as soon as possible after inoculation. If the seeds are too wet and stick together, mix them with a little dry earth or sand till they are dry enough to drill.

6. The seed should be drilled and not broadcast, as it must not rest on the surface of the ground, because light kills the bacteria. For this reason, also, the inoculated seed must not be exposed to the sun before drilling.

N.B.—The required amount of calcium phosphate is enclosed with the cultures. This should be dissolved in the milk before the bacteria are added.

Chapter V

THE SOIL AND THE LIVING PLANT

We have traveled a long way from the simple views of plant nutrition current eighty years ago, with which these lectures opened. It is now known that the nutrition of the plant, like everything else in nature, is very complex and affected by many factors besides the actual nutrients themselves. A complete discussion of the subject lies beyond the power of any one man because it involves so many other sciences: it would indeed almost necessitate the writing of an encyclopedia.

> One grass blade in its veins
> Wisdom's whole flood contains.

But our discussion would be very inadequate unless we try to obtain some picture of the structure and composition of the soil, the system in which all these changes take place.

The greater part of the soil is derived from the solid rock of which the crust of the earth is formed. For various reasons the surface of the rock splintered; particles were broken off and either blown or washed into some new position which they now occupy: a certain amount of chemical decomposition also took place. The result is a mass of rock fragments of varying sizes and shapes, and in varying degrees of decomposition. Some of these decomposition products are jelly-like or colloidal in character: these stick to the solid rock fragments or form little aggregates of their own. This is the skeleton of the soil, but it is not yet the soil itself. A great change sets in as soon as plants arrive.

During their lifetime plants absorb soluble salts from the soil and carbon dioxide from the air, building them up into complex substances. The process is sufficiently remarkable, but the most fundamental change from our point of view results from the fact that these substances contain energy derived from sunlight. When the plants die their residues fall back on the weathered mineral mass, returning the nutrients taken up during their lifetime and in addition supplying organic matter and energy material not there before. It is this that distinguishes 'soil' from 'disintegrated minerals.' Nature is so bountiful of life that wherever conditions permit of life there it seems to occur. Along with the energy material is found a population of microörganisms, and these, in obtaining the energy and nutrients necessary to their own growth, produce the simple substances that serve as nutrients for the next generation of plants. This then completes the *soil.*

Soil thus contains two phases: the mineral phase, resulting from the disintegration and decomposition of the rock; and the organic or energy phase resulting from the residues of plants that have grown there in the past. These two phases allow the development of the population of living organisms which we must regard as one of the characteristic features of the soil.

The composition of the mineral phase is obviously dependent on that of the rock. But both the mineral and the organic phases are also profoundly affected by the climate. In humid cool conditions the silicates break down to form soils rich in silica (SiO_2), some of the bases tending to be washed downwards. But in wet tropical conditions the silica is dissolved out (the water apparently being alkaline), leaving only the iron and aluminium oxides, while in still wetter conditions the

aluminium oxide disappears, leaving only the iron oxide which forms the 'laterite' soils of the tropics.

The nature of the organic matter is determined by the vegetation from which it arose and the decomposition to which it has been subjected in the soil, both of which are dependent on the climate.[1] Thus the soil is very much the child of the climate, and, as C. B. Lipman and D. D. Waynick showed, if a soil is carried to a new district its properties may change: in seven years they found considerable alteration.[2]

The first great division of soils therefore is into the laterites and the silicate soils. Further divisions of the silicate soils depend on whether they have suffered much or little decomposition or, what comes to the same thing, whether the decomposition products have been able to accumulate or whether they have been eroded away: in the former case there may be considerable colloidal matter present; in the latter the soil is simply disintegrated rock.

Another great division is determined by the presence or absence of reactive *calcium*. In the realm of nature it is remarkable how exceedingly important certain elements are in comparison with others. Probably no single element plays a greater part in the soil economy than does calcium. The whole flora of a soil, its agricultural possibilities and therefore the comfort and well-being of the agricultural community that dwell upon it, are all

[1] A good example is furnished in the soils of Java and Sumatra recently studied by E. J. Mohr (De Grond von Java en Sumatra, Amsterdam, 1922). Where the soil temperature is below 20° C., humus accumulates, being formed faster than it is decomposed: in the lowlands where the soil temperature exceeds 30° C., the decomposition proceeds faster than the formation, consequently there is no humus: at about 25° C. the soil humus remains steady in amount.

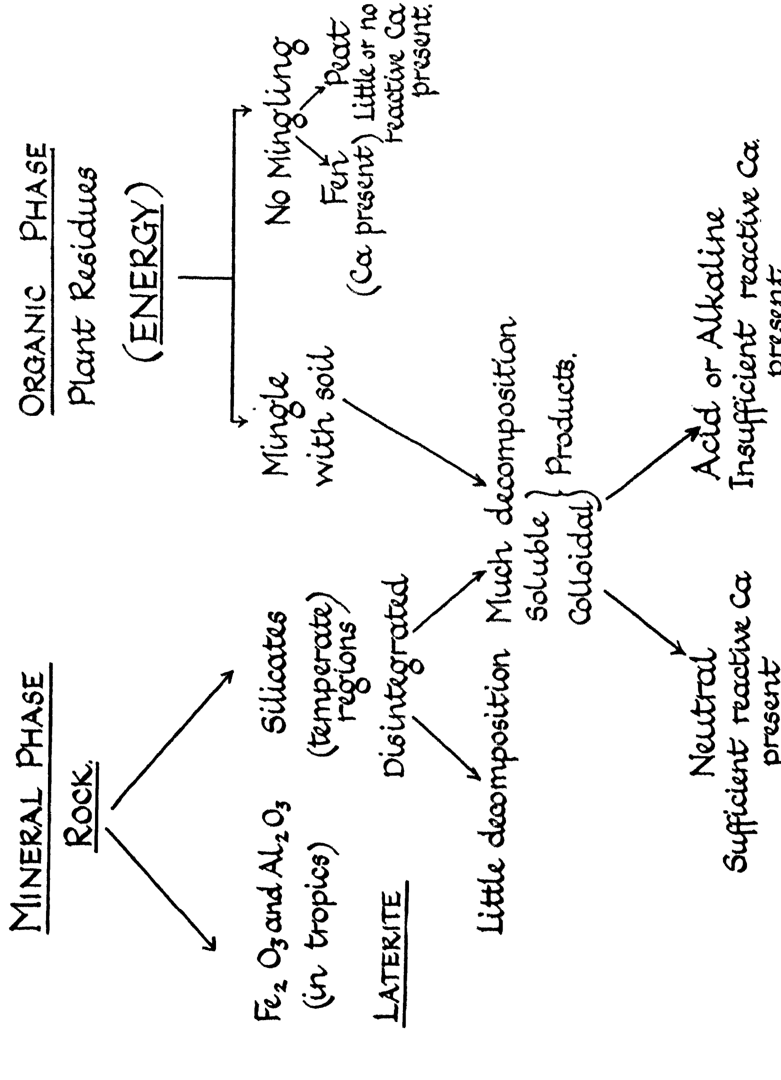
[2] Soil Science vol. 1, pp. 5–48 (1916).

profoundly affected by the consideration whether it does or does not contain reactive calcium.

A third great soil division depends on the fate of the organic matter: in the normal case, it mingles with the soil, being drawn in by earthworms, ants, or other animals but when mingling agencies are absent it lies on the surface and forms peat, fen, or muck soils.

Time does not allow of consideration of the laterites, the peats, or the fen soils. We are concerned mainly with the great middle region in the scheme of figure 33; where the decomposition products have persisted so that colloidal substances are present; where there may or may not be much reactive calcium, but where there is invariably organic matter, the remains of older generations of plants, which have decomposed so far as to reach the steady state discussed in the preceding chapter. Reference has already been made to the fact that some of the soil constituents are in the jelly-like or colloidal condition. The soil particles are pictured as being coated with jelly just as if they had been steeped in it. The study of the soil colloids is one of the triumphs of modern times and is furnishing the explanation of many important soil properties which had previously been wholly inexplicable.

Tilth is one of the chief properties dependent on the colloids. It is easier to recognize in the field or garden than to describe, but it indicates the good crumbly condition into which soil must be got before the young plant has much chance of successful growth. Farmers have learned by long experience how to obtain a tilth, but the process is costly and often tedious. Science has as yet been able to offer no help and little information; the position resembles that of manuring in 1830: our knowledge is vague and uncertain and of little practical assist-


MINERAL PHASE
ROCK
Fe$_2$O$_3$ and Al$_2$O$_3$
(in tropics)
LATERITE
Silicates
(temperate regions)
Disintegrated
Little decomposition
ORGANIC PHASE
Plant Residues
(ENERGY)
Mingle with soil
No Mingling
Fen
(Ca present)
Peat
Little or no reactive Ca present.
Much decomposition
Soluble
Colloidal
Products.
Neutral
Sufficient reactive Ca present
Acid or Alkaline
Insufficient reactive Ca present

ance. Investigations are now going on at Rothamsted and elsewhere to find exact physical expressions for tilth, the measurements at present under investigation being resistance to the plow in the field, and moisture relationships and plasticity in the laboratory. Only the future can show whether these will lead to developments in the way of scientific cultivation of the same order of importance as the artificial fertilizers which grew out of the statistical work of Boussingault, the generalizations of Liebig, and the pot and field experiments of Lawes. But all past experience shows that the safest way of ensuring progress is to define and measure exactly the thing one wishes to study, and the work in soil physics which has this for its object may, in spite of its remote and academic appearance, yet prove the shortest way to the solution of very difficult practical problems.

One of the first fruits of the physical investigation has been the discovery of a simple means whereby the resistance of the soil to the plow could be reduced. The soil colloids are electronegative: if therefore a negatively charged plate is inserted in the soil the colloidal particles will tend to move away from it leaving only the water on the plate. Now a film of water is an almost perfect lubricant. If therefore the plowshare is kept negatively charged it becomes coated with a film of water, and therefore continuously and perfectly lubricated, so that it moves through the soil with less resistance than before. The maintenance of an electric charge is not in principle difficult: it necessitates taking current from the tractor drawing the plow. Practical difficulties have still to be overcome, but the nature of the effect is illustrated by the curves in figure 34.

Several other important properties are dependent on the colloids. They are partly, at any rate, responsible

for the remarkable power possessed by the soil of absorbing dissolved substances from solutions. It is reasonable to expect that they therefore play some part in the curious phenomena associated with the intake of plant nutrients from the soil—a process now being studied at the University of California, and which, like the process of absorption of carbon dioxide from the air, requires the addition of energy for its completion.

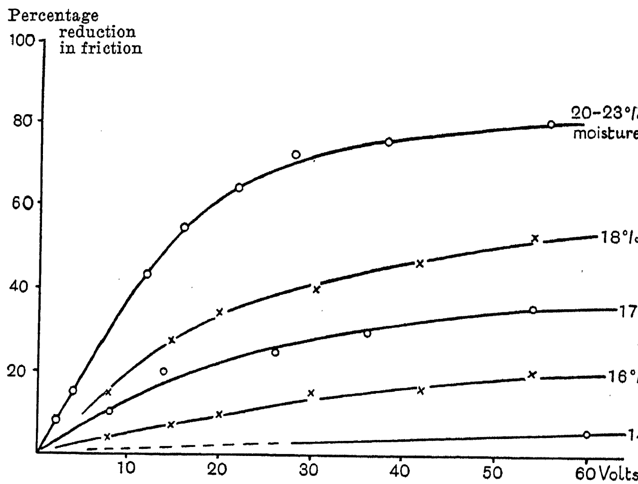


Fig. 34. Effect of electric current on soil friction. E. M. Crowther and W. B. Haines, Jour. Agr. Sci., vol. 14, p. 221 (1924).

There is also reason to suppose that the soil colloids profoundly affect the lives of the soil microörganisms. It has long been known that soil effectively filters out bacteria from liquids passing through it. Cutler has shown that soil completely absorbs protozoa from a suspension till a certain saturation point is reached after which it takes up no more. The numbers absorbed are small only in comparison with the total surface of the soil: the estimate is necessarily very rough, but while a

gram of soil has a surface of the order of 2500 sq. cms., the area of the absorbed amoebae and flagellates is only about 4 sq. cms. Apparently only a small portion of the soil is concerned in the action, and the simplest assumption is that it is effected by the soil colloids. On this view the soil microörganisms, especially the larger ones, may be supposed to live and move on the surface of the colloidal jelly. From this they would not easily be detached, hence the failure of many of the direct microscopic examinations to reveal them.

Comber has put forward the interesting suggestion that the soil colloids play a direct part in plant nutrition. He supposes that the colloidal coating of the plant rootlets mingles with the colloidal coating of the soil particles and thus incorporates within itself part of the absorbed insoluble materials: phosphates, potassium, and other compounds important as nutrients can thus be absorbed without the necessity for going into solution. The idea merits careful consideration as it has important bearings on soil solution studies and on soil analysis.

Many efforts have been made by chemists to find out something about this remarkable jelly-like material. It is unusually difficult to investigate, and apparently it is not the same in all soils: the ratio of silica (SiO_2) to alumina (Al_2O_3) varies, and there is some evidence that the variation is associated with changes in physical character and fertility (table 13). Bradfield's attempts to make the soil colloid artificially by mixing colloidal silica, alumina, and ferric oxide in the right proportions were not successful, and the indications are that the natural substance is a complex alumino-silicate.[3]

[3]See Bradfield, Missouri Agr. Exp. Sta., Res. Bull. 60 (1923). Considerable quantities are being prepared at the U. S. Bureau of Soils, at Rothamsted, and elsewhere, by means of the Sharples supercentrifuge, and further investigations will soon be made.

The difficulty of the chemical examination is much increased by the fact that soil contains reactive bodies which absorb or precipitate certain ions and which may be, but are not necessarily, the same as the soil colloids. These bodies were brought into prominence in 1852 by Way, one of the most ingenious-minded of English agricultural chemists, who was following up an observation made by a country gentleman having some chemical knowledge, H. S. Thompson, of Moat Hall, York, who later became Sir Henry S. Meysey Thompson, a leader

TABLE 13. COMPOSITION OF CLAY ("ULTRA-CLAY"), AND ITS PROPERTIES

	Ratio $\frac{SiO_2}{Al_2O_3}$
English soils:	
Fertile	2.5
Less fertile	1.6
Very plastic (Joseph)	3.9–4.8
Less plastic	2.8
Non-plastic (Kaolinite and China clay)	2.0

among England's agriculturists. Thompson wished to examine the possibility that soil might stop the waste of ammonia from manure heaps and stable runnings, and he suggested to a chemist friend, John Spence, a Quaker of York, the desirability of testing the power of soil to absorb ammonia.[4] The experiment was entirely successful. Way heard of the result, and attributed the absorbing power to certain double silicates which he assumed to exist in the soil and to react by ordinary double decomposition with the ammonium salt.

This view held the field for nearly forty years till Van Bemellen, the first of the distinguished Dutch agri-

[4] Thompson's experiments were made in 1845: his account is in the Jour. Roy. Agr. Soc., vol. 2, p. 68 (1850); a memoir of him by the Earl of Cathcart is in the same Journal, vol. 10, p. 519 (1874).

cultural chemists to work in Java, adduced evidence in 1888 that the reactive bodies are simply absorption complexes containing silica, iron oxide, alumina, etc., all loosely absorbed, but not definitely combined. The facts of base exchange, studied by Bradfield, Kelley, Hissink, and others, show that there is some kind of chemical combination, since the absorption or precipitation effected by the reactive bodies is accompanied by the giving up of an equivalent amount of base just as in normal double decomposition. The view most in accordance with the facts is that the reactive constituents of the soil are compounds of alumino-silicic acid, and that they form a large part of the colloidal material.

The calcium body—which we may call the calcium complex in order to avoid committing ourselves to the unproved view that it is calcium alumino-silicate—is of fundamental importance to soil fertility. It alone seems to confer upon the soil the property of going into a desirable tilth. It is easily converted into a sodium complex by continued washing of the soil with a solution of sodium chloride or sodium nitrate, and the soil then completely changes its character: a sandy or gravelly soil becomes like concrete: a clay becomes a hopelessly sticky mass. If by some catastrophic blow all the calcium were removed from soil the face of the earth would be greatly altered.

A contingency of this magnitude is improbable, but smaller changes are of common occurrence. The flooding of land by sea water is liable to injure it considerably through the interaction of the salt and the calcium complex. The use of irrigation water containing sodium salts in solution—a not unusual occurrence—leads to a gradual substitution of calcium for sodium, with a concomitant deterioration of the soil properties familiar to

everyone in irrigated regions; worse still, the sodium complex, being a salt of a very weak acid, tends to hydrolyze and give rise to sodium carbonate, the dreaded "black alkali," perhaps the most terrible of all soil scourges. The remedy is to get back the calcium complex and to withhold sodium salts, but unfortunately this is too often only a counsel of perfection and cannot be carried out in present circumstances.[5]

Another change occurs in wet conditions. The calcium complex, being hydrolyzible, gradually decomposes in presence of the large quantity of rain water and carbon dioxide, forming a hydrogen complex and calcium bicarbonate which washes out. If now a solution of a sodium or a potassium salt with a strong acid (e.g., hydrochloric or sulphuric) is added, a double reaction takes place: the potassium combines with the hydrogen complex forming a potassium complex and displacing the hydrogen ion: the acid radicle combines with the aluminium oxide forming aluminium chloride or sulphate which goes into solution. Now soluble aluminium salts are poisonous to plants, and a system containing hydrogen ions in excess of hydroxyl is acid. In these circumstances, therefore, an acid soil arises, with a measurable hydrogen ion concentration, and toxic to plants. This trouble is known as 'sourness' or 'acidity' of soil: it is common in wet temperate or cold regions, and in these conditions is probably as serious for the cultivator as is alkali in the warm dry regions (fig. 35). Fortunately, the remedy is simple: it is to add sufficient lime to precipitate the soluble aluminium salt and reduce the hydrogen ion concentration to a tolerable quantity. Electrometric methods for measuring the necessary quantity of

[5] Hissink explains in this way the alkalinity ($pH > 8$) of the "Kwelder" soils, i.e., those reclaimed from the sea in Holland.

lime are in use in well-equipped soil laboratories and as experience ripens it will be possible to advise the farmer with precision, enabling him to reduce his expenditure to a minimum—an absolutely indispensable condition nowadays. Numerous short cuts have been devised but they are apt to be broken down by the 'buffering' action of the soil.

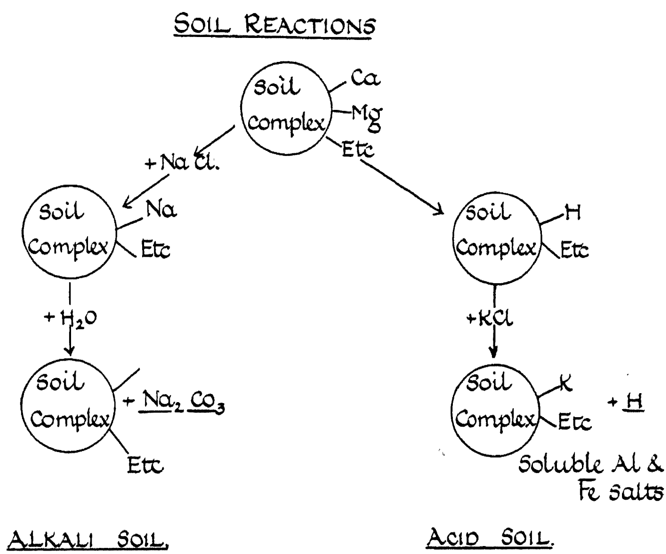


Fig. 35. Results of reactions of soil complex.

These ideas on the calcium complex and its relation to soil alkali and soil acidity are largely due to Gedroiz, a distinguished Russian chemist, who put them forward in 1912 in the Russian Journal of Experimental Agriculture. As few people read that language, the ideas remained unknown to most scientific workers. A translation of the papers has now been made by Waksman for the Bureau of Soils and they have thus become accessible.

On this view alkalinity and acidity are simply different phases of one and the same chemical property of the calcium complex. The idea would have been unthinkable a generation ago when the two properties were regarded as wholly disconnected; it has, however, recently been demonstrated by Cummins and Kelley[6] in one of the simplest and most elegant experiments in agricultural science. An acid soil was washed with a solution of sodium chloride to form the sodium complex: it was then washed with water whereby sodium carbonate was produced: the acid soil was thus converted into an alkali soil.

In addition to these big mass changes, there are others much more local. Our present experimental methods do not allow these changes to be followed, but a first approximate idea of their nature may be obtained by applying the principles and reactions brought out above. It has already been shown that, from day to day and from hour to hour, the soil organisms vary in their activity, producing carbon dioxide, nitrates, and other substances. Now every change in the amount of nitrate involves a rearrangement of the calcium and other bases. Further, the plant root daily absorbs nitrates but it does not appear to retain the salt as a whole: there is some differential retention and part of the base is left behind or excreted after absorption. The carbonic acid is in all probability produced very locally and therefore its concentration and its action on the bases varies locally. These reactions affect all the bases and cause constant changes in their grouping.

The study of the soil complexes is one of the most fascinating problems for the future. The present investigations on basic exchange may reveal a good deal but

[6] California Tech. Paper, No. 3 (1923).

there are even greater hopes from the applications of physical methods. It is possible that the use of X-rays might teach as much about the structure of soils as in the hands of Sir William Bragg and his son they have taught about the structure of crystals.

It has already been stated that the soil particles are irregular in shape and that by cultivator's art they can be grouped to form the crumbly condition known as tilth. The soil as a whole is therefore not completely solid: it contains much continuous pore space. These pores of course are not empty but are filled partly with air and partly with water: the volumes at Rothamsted are as follows:

VOLUMES OF AIR, WATER, AND ORGANIC MATTER IN 100 VOLUMES OF ROTHAMSTED SOIL

	Solid matter		Pore space	In pore space	
	Mineral	Organic		Water	Air
Arable land, no manure	62	4	34	23	11
Arable land, 10 tons dung given annually	51	11	38	30	8
Pasture	41	12	47	40	7

The rate of diffusion of gases is fairly considerable and it is perhaps not surprising that the atmosphere of the soil should approximate to that of the atmosphere we breathe: some typical analyses are:

	Per cent by volume		
	Oxygen	Carbon dioxide	Nitrogen
Arable land, no manure	20.4	0.2	79.4
farmyard manure	20.3	0.4	79.3
Grass land	18.4	1.6	80.0
Atmospheric air	20.9	0.03	79.1

The oxygen is usually not unlike that of our atmosphere in amount; the carbon dioxide, however, is commonly some ten or twenty times greater. Plants vary in their reaction to carbon dioxide at their roots: some tolerate it more than others; the usual concentration of carbon dioxide in the soil air is thus a factor in determining their distribution, and it probably plays an important part in limiting the flora of a clay soil. In a water-logged soil the air may be wholly displaced or so entrapped that diffusion is greatly retarded; the percentage of oxygen may then fall considerably, bringing about a second kind of effect, an actual asphyxiation of the plant root; few plants can tolerate this treatment.

The sizes of the pores determine the rapidity of air exchange, so that it is greater in some soils than in others. The details of the relationship are studied in soil physics. The general effect on plant growth is shown in plate 21A.

Control of the composition of the soil atmosphere is effected by drainage, which removes water from the pore spaces and therefore allows the admission of air; by cultivation, which increases the size of the pore spaces; and by the introduction of porous material, such as potsherds, which has been recommended by the Howards in India.

Water is the other occupant of the pore space. It is held to the soil by three kinds of forces: gravity, capillarity, and the more intimate forces of chemical affinity. For purposes of convenience the soil water is sometimes divided into three parts called, respectively, gravitational, capillary, and combined; but this is an artificial distinction and, like all such, is fraught with a dangerous tendency to loose thinking unless severe self-discipline is imposed. As Shull has proved, there is no break in

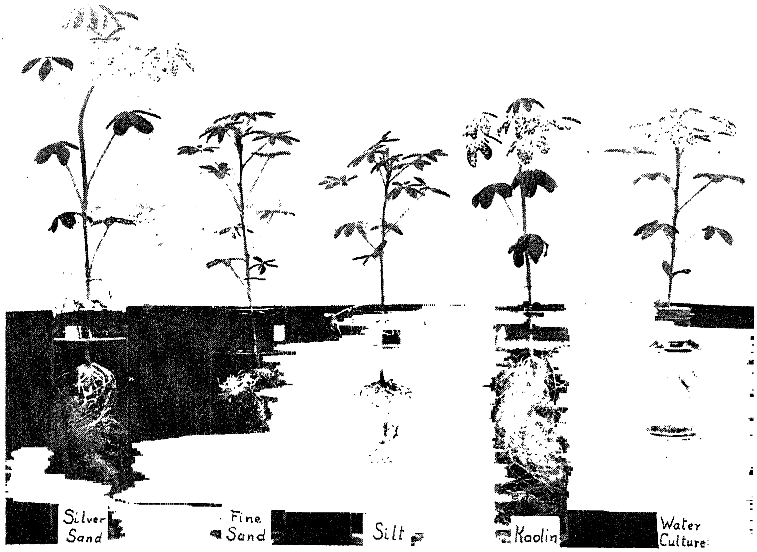


PLATE 21A. Plant growth and soil pore space (A. D. Hall, W. E. Branchley, and L. N. Underwood, Phil. Trans., vol. 204, pp. 179–200, 1913).

PLATE 21B. Feeding sheep on growing crops: a useful method of adding organic matter to the soil.

the state of the water, but a gradual insensible transition from the water mainly held by gravity to that mainly held by affinity (fig. 36). In natural fertile conditions a considerable part of the water is held by forces of the order of 1000 times that of gravity—approximately one atmosphere—and in these circumstances plants seem to

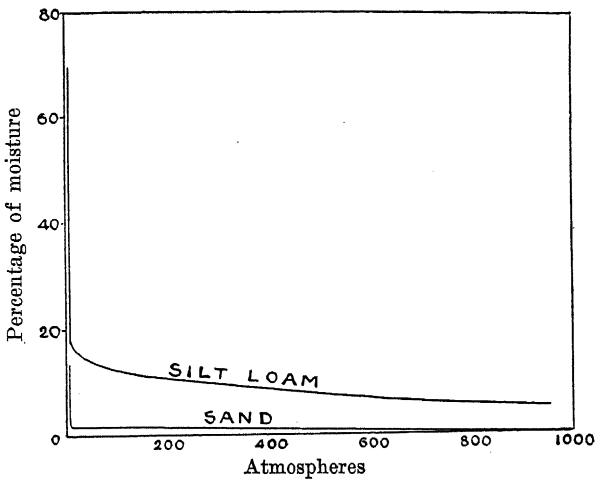


Fig. 36. Magnitude of force with which water is held by soil, showing change with decreasing water content. C. A. Shull, Bot. Gazette, vol. 62, p. 1 (1916).

have no difficulty in obtaining supplies. By the arts of soil management it is possible to increase the pore space and the proportion of water retained by forces of the proper order.

Control of the moisture relationships of plants is effected in practice in several ways: (1) by adding more water: irrigation or subirrigation; (2) by reducing losses of water: done by keeping down weeds; by cultivation; by increasing the amount of colloidal matter: in practice organic matter (pl. 21B); and by possible modifications in

colloidal properties. As always happens, the agriculturist seeks to lighten the burden of artificial control by a third method; (3) using crops or systems of husbandry specially suited to the existing conditions.

The final phenomena for discussion are connected with the circumstance that the soil water is never pure but is a solution containing some of all the soluble substances in the soil: its concentration is usually of the order of 0.1 to 1.0 per cent in cropped soil but is higher in fallow soils. The significance of the soil solution as the nutrient medium for growing plants was first pointed out by Milton Whitney, and the knowledge of the soil solution is largely due to investigators in the United States, of whom one of the first was F. D. Cameron and some of the latest are the workers at the University of California. The earlier workers regarded the soil solution as being saturated with the minerals composing the soil, and as these are not widely dissimilar over large areas they expected to find a substantial degree of uniformity in composition. It is now known that this simple view is not correct: the composition of the soil solution is greatly modified by the reactions effected by the microorganisms, the reactive silicates, and the absorption by the colloids and the growing plant. The Californian group, Charles Lipman, Hoagland, Burd, Stewart, Martin, Sharp, and others are studying the variations in composition of the soil solution: they have shown how it changes from time to time and how it is affected by the growth of plants (fig. 37). If it were found possible to link up this work with studies of microörganic activity in the soil we might hope for a fuller picture than has yet been attained of the sum of the changes going on in the soil. We should still need micro-methods for following out the reactions in detail: for the changes are not

effected uniformly throughout the mass of the soil but are more probably localized on the colloidal surface or in the organic matter. But there is no suggestion yet of any way of doing this and meanwhile there is much to learn from present methods. For if we assume that the

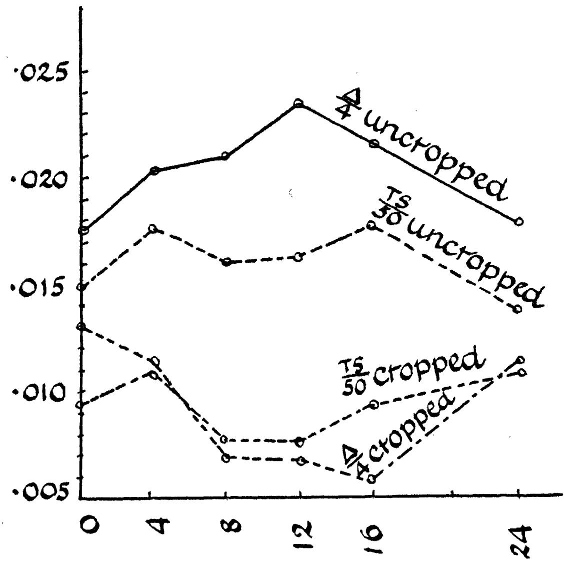


Fig. 37. Concentration of soil solution in silty clay loams, cropped and uncropped. Hoagland, Martin, and Stewart, Jour. Agr. Res., vol. 20, p. 381, 1920. (T.S. = 1:5 water extract. Δ = Freezing point depression. Moisture = 22 per cent.)

soil solution is of prime importance for the nutrition of the plant, as on current views it is, the object of scientific manuring becomes the maintenance of the soil solution at the optimum concentration for the crop, and this object is by no means impossible of attainment.

We can now summarize the position at which we have arrived. The nutrients of plants fall into two great

groups: the carbon dioxide supplied from the air, and the simple salts obtained from the soil. The elements of these salts also form two groups: those needed in large quantities as constituents of the plants (nitrogen, phosphorus, potassium, etc.) and those needed only in minute amounts, apparently serving as catalysts, stimulators, or directive agents—manganese, boron, and others, possibly also certain organic substances. The plant responds to variations in supplies of these nutrients: not only is the total growth affected but the composition of the cell sap changes and with this come changes in the habit of growth, in the leaves, the root system, the rate of ripening, the feeding value, the suitability to insect and fungus pests. The degree and to some extent the nature of the response depend on the soil and climatic conditions: the plant, the soil, and the climate are so completely interdependent that it is unwise to think of one apart from the others. Variations in nutrient supplies are within the control of the farmer through the numerous artificial fertilizers now available.

In nature, and to a very large extent in farm practice, the plant is dependent on the soil for its supplies of nutrients. These exist in the soil in small quantities but they are perpetually being formed there as a result of chemical actions. The raw materials are the dead residues of previous generations of plants: the agencies bringing about the changes include myriads of microorganisms living in the soil. A wonderful cycle goes on: the plant grows, absorbing carbon dioxide from the air and the simple salts needed for its nutrition from the soil: these are built up into the complex substances of which the plant is composed. A considerable amount of energy is required for these processes and this comes

from sunlight, which the plant is able to utilize—a feat no modern engineer can yet emulate. When the plant dies its residues mingle with the soil: they still contain some of the energy that has been fixed and the elements constituting plant nutrients. These residues furnish food and energy to the soil population which is so diverse in character that its various members can apparently utilize all the available energy. In the process they produce the nutrients required by a new generation of plants: they also clear the soil of organic residues which would be harmful to plant life. Thus plants and micro-organisms are mutually dependent: the plants fix energy which the microörganisms utilize, and the microörganisms produce nitrates and simple salts which constitute plant nutrients.

This process of plant food production is continuous but it is not uniform. The activity of the microörganisms fluctuates from day to day and from hour to hour, with the result that the quantity of nitrate presented to the plant roots is continuously liable to change. How the plant has adapted itself to this fluctuation is not known.

All these changes go on in the soil. But the soil is not a passive medium: it is an active participant. So far as proportions by weight are concerned it is formed chiefly of rock fragments which are relatively inert, but it also contains colloidal substances, presumably as a coating on the rock fragments, which confer on it properties of absorption, tilth formation, and others important to the growing plant: it contains substances capable of reacting with salts to produce double decompositions which according to circumstances, may give rise to soil alkali or to soil acidity. Whether these substances are identical with the colloids is not known but there is evidence that

the calcium complex, possibly calcium alumino-silicate, plays a highly important part, for the soil deteriorates considerably as a medium for plant growth when the calcium is replaced by sodium or other bases. Calcium is thus elevated to a unique position among the elements, for when it is absent soil fertility as we know it ceases to exist.

The crop growing in the field is the resultant of all these various actions. Obviously it is beyond human ability to put all these factors together and predict the result. But the investigations have shown what the factors are, and have given much knowledge about the soil and the growing plant. Already some of this has been applied to the problem of lightening the farmer's tasks and increasing his yields. But its value goes far beyond this purely materialistic end: it has furnished the teacher with principles and facts that he can utilize for drawing up a sound system for training the young people in the countryside, and it has shown to the countryman something of the infinite wonder of the things he handles daily. The past has been rich in the joys and thrills of discovery; but it has taught this lesson: that discoveries in applied science inevitably follow advances in pure science. If we would improve our agriculture the surest way is to increase knowledge of the soil, the plant, and the animal. Empirical methods, it is true, have often given advances in the past, but they are slow, hesitant, and uncertain; dependent on accident. Exact knowledge is the only sure basis for improvements; encourage, therefore, those among you who are striving to win it. Their task is slow, painful, and often disappointing. To know all, even about the simplest thing in nature, is beyond human achievement;

knowledge is but an approximation to a truth that can never be wholly attained by man. These investigators are doing great work; it is man's nature to explore, leaving the known, and pushing out always into the unknown.

> . . . . Man's the prerogative, knowledge once gained
> To ignore, find new knowledge to press for, to swerve
> In pursuit of, no! not for a moment: attained,
> Why, onward through ignorance! Dare and deserve!
> As still to its asymptote speedeth the curve.